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UNITED STATES
DEPARTMENT OF THE INTERIOR
J. A. KRUG, SECRETARY

BUREAU OF MINES
R. R. SAYERS, DIRECTOR

INFORMATION CIRCULAR

WHAT IS COAL?

BY

REINHARDT THIESSEN

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By Reinhardt Thiessen[2]

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INTRODUCTION

Coal is a complex substance consisting of many different constituents representing many chemical compounds, very few of which are known. It is homogenetic, however, in that it is derived almost entirely from plants. But plants as a whole are complex, being composed of a large number of tissues, each consisting of a large number of cells in a great number of arrangements and composed of a number of chemical compounds in great variety of proportions, and enclosing a large number of waste products representing a large number of chemical compounds as cell contents. Coal should therefore be expected to be a very complex substance.

That coals are formed from plants is no longer debated, but the manner in which coal was formed from the plants leaves many problems still unsolved. However, in general it is now conceded that all coals of all ranks and ages had their origin in deposits completely analogous to our peat deposits of today and that coal formation is a process that runs through the whole series, beginning with peat, and through the various ranks of lignite, subbituminous, high-, medium-, and low-volatile bituminous, semianthracite, and anthracite in a related chain. In the study of coal, it is therefore of the utmost importance to study and to know not only the plants contributing but also the manner in which they are transformed into the substances forming the deposits. It is therefore of the greatest value to review briefly the formation of peat as it is known today, and to inquire into the facts as to what plants contribute to peat, what parts and products prevail, what are the chemical compounds that enter and which prevail.

HOW PEAT IS FORMED

Peat is formed, usually, in more or less shallow, undrained depressions or plains with environments favorable to luxuriant growth. Great moisture, retained through poor drainage, and the maintenance of luxuriant growths of micro-organisms are the most essential factors. Many types of peat deposits are recognized, such as marsh, high-moor, low-moor, fen, and wooded swamp, each one depending on various factors, such as nature of the depression, form and size of the basin, nature of the banks and underlying rock or soil, climate, such as length of seasons, precipitation, temperature, wind, etc., physiography of the surrounding country, providing kinds of outlets and inlets, and altitude and latitude. It may be seen from these factors that the matter may be very complicated and the resulting deposits may differ greatly.

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PLATE I

Fig. 1. Landscape view of peat swamp in Manitowoc and Calumet Counties, Wisconsin, looking west from an island in the swamp. The hills seen in the distance are approximately 10 miles to the west.

Fig. 2. Interior view of an aboriginal part of the swamp.

Fig. 3. A cedar tree fallen over to show the shallow root system.

Fig. 4. A close-up view of the interior of the swamp to show its general nature. Notice the water in the foreground reflecting the trees in the back, the hummocks, the half-buried trees and other debris on the surface, and particularly the lack of herbs and shrubs.

Fig. 5. A closer view of part of the same area showing the smaller twigs and stems.

Fig. 6. A still closer view of about the same area showing the very small twigs, shoots, cedar leaves, and general debris.

Fig. 7. A transverse section of a young pine shoot to show its general structure and cell contents. p - pith; w - wood cylinder; ca - cambium; ph - phloem; co - cortex; phn - phellogen; ep - epiderm; rd - resin ducts or reservoirs; lf - leaf; magnification about 25 diameters.

Fig. 8. Diagrammatic representation of the wood of a broad-leaved tree, showing the relationship of the transverse, radial, and tangential sections. a - pith; b and c - medullary rays on the radial surface; d - medullary rays on the tangential surface; g - groups of vessels; i - summer wood; aa - radial longitudinal section; dd - tangential longitudinal section; iai - transverse section. (Fig. 115, The Microscopy of Technical Products, by Hanavsek - Winton, 1907.)

Fig. 9. Transverse section of pine wood. tr - tracheids or wood fibers; rd - resin duct or reservoir; ra - medullary ray; ar-ar- - annual ring. X50.

Fig. 10. Radial section of pine wood. tr - tracheids or wood fibers; ra - medullary ray; bp - bordered pits in the wood fibers. X50.

Fig. 11. Tangential section of pine wood. tr - tracheids or wood fibers. ra - ends of rays on the tangential surface; bp - cross sections of the bordered pits in the radial walls of the wood fibers. X50.

Fig. 12. Transverse section of a 1-year old shoot of the bald cypress. p - pith; w - wood cylinder; ca - cambium; ph - phloem. The dark outer rim represents dead phloem or outer bark; the dark spots represent resinous and tannic cell contents. X12.

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Plate I

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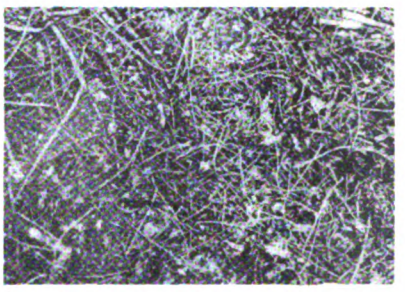

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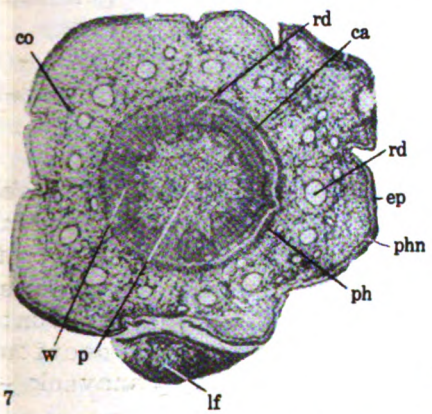

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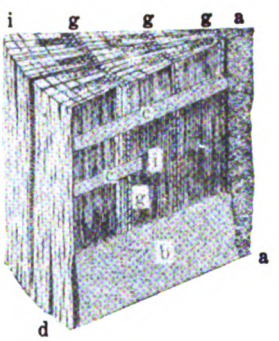

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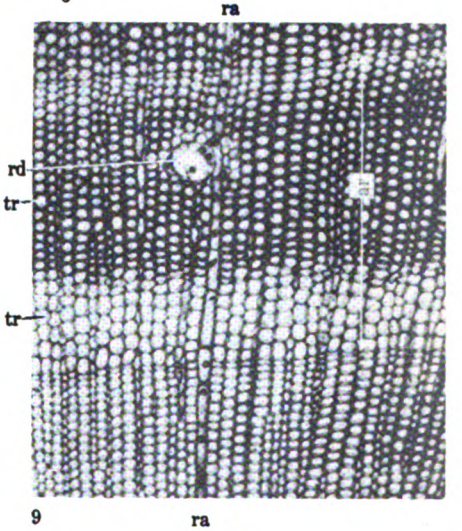

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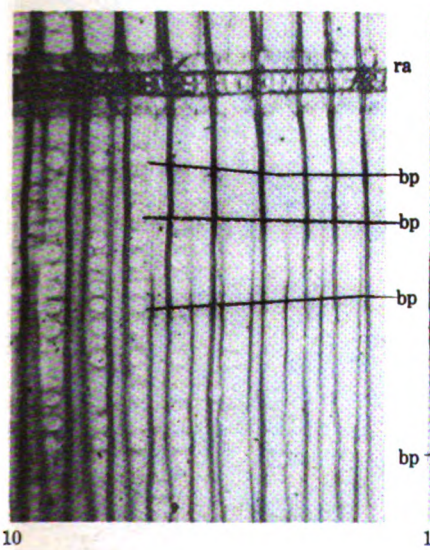

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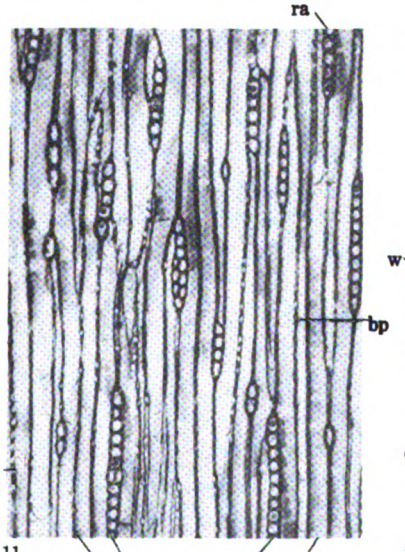

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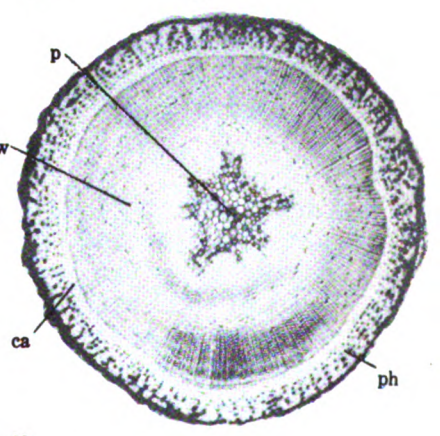

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Of the many types of peat, the woody peat or peat derived from the wooded swamp is the more common and, according to all evidence, was similar to the ancient peat swamps that gave rise to the more common types of coal. We shall confine ourselves in this discourse to this kind and take the wooded peat swamps of Wisconsin as an example.

Figure 1, plate I, shows in the distance one of the Wisconsin peat swamps approximately 20 square miles in extent. Considerable areas have been cleared of the original growth in recent years; other parts have been cleared earlier and are now covered by a second growth; other areas are still covered with the aboriginal forest. (Fig. 2, plate I.) The growth consists very largely of the white cedar, with only an occasional tamarack, spruce, balsam, or black ash among them. In other words, it is almost completely coniferous. The growth of both the second and the aboriginal is so dense that light is excluded to such an extent that it does not permit underbrush and herbaceous plants to grow; mosses, lichens, liverwort, and fungi, however, abound in profusion.

A swamp of this kind is awe-inspiring and puts one in a peculiar frame of mind. With the sunshine trickling through the leafy branches but sparingly, a twilight condition prevails even at high noon under a clear sky; almost semidarkness prevails on cloudy days at noon. A breeze is manifested only by a sigh in the treetops, a gale by a howl or a moan and the creaking of tree trunks and branches rubbing together. On calm days, the silence is distressing, interrupted only by an occasional gargulous shriek of a blue jay, the chirp of a nuthatch, or the caw of a crow overhead, or the doleful hoot of the owl at lowering sun. The beauty of the surroundings, no matter what time of the year, is one of grandeur. In some places all the trees stand straight (fig. 2, plate I); in others, the wildest entanglement of broken down or reclining trees exists. Normally, the surface is very wet, submerged for the most part during wet seasons, and thoroughly soaked with water even during the dryest periods. (Fig. 4, plate I). Walking is difficult, and progress can normally be made only by jumping or stepping from hummock to hummock. A jump or step short of the mark leaves the visitor deep in a pool of water or mire.

The roots of the trees remain close to the surface. When the root system becomes too deeply covered by the debris of the ensuing years the tree dies, soon falls over, and becomes water-logged. Also, because of the insecure hold of the roots upon the loose deposit, trees are easily blown over. Figure 3, plate I, shows a cedar tree blown over, revealing a closely woven, flat, shallow network of roots.

Figure 4, plate I, shows the interior of a swamp in its normal condition. Water covers the foreground, and many hummocks and depressions filled with water may be noticed in the background. The litter consists of tree trunks partly buried, some totally buried, indicated by ridges, smaller stems, branches, and twigs. Figure 5, plate I, represents a closer view, in which are distinguishable fragments of small stems, twigs of all sizes, and a few leaves. Figure 6, plate I, represents a still closer view, looking directly down, and representing only about one square

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foot. In this are distinguishable small fragments of wood, very small twigs and shoots, petioles, and numerous cedar leaves. Great emphasis is to be laid on this small material, almost all of which is of coniferous origin, recognized on the surface as an important contributant to peat.

THE STRUCTURE OF A CONIFER

In order to realize fully what is actually contributed by this coniferous growth, knowledge of the structures, products, and chemical nature of the conifers in general is necessary. The little twiglet so abundantly found on the surface will be used as material for illustrations.

It should be stated at the outset that all woody peats studied up to this time were derived predominantly from coniferous plants; also, that all the younger coals studied, from the Pleistocene to the Cretaceous, were almost entirely derived from coniferous plants; further, that all the older coals studied were also largely derived from conifers; and that only the remains of lycopods and cycadophytes seriously compete with them.3/ The conifers, it appears, then, were important coal-forming plants, and a knowledge concerning them is of the utmost importance in the study of peat formation. For the present, we need pay attention to the conifers only.

THE TREE AND ITS PARTS

The tree, such as the pine, spruce, balsam, and others, is made up of three distinct parts, called its organs; these are stem, roots, and leaves. (The branches are classed with the stem.)

The main stem is called its trunk. The trunk has many branches that branch and rebranch, each of which has a structure similar to that of the trunk or main stem. Both trunk and branches, as also the roots, increase in thickness and in length during their lifetime, and both are built up of a number of tissues. From the center out, these are pith, xylem or wood, and bark. The bark, in turn, consists of phloem, pericycle, endoderm, cortex, and epiderm. (Fig. 7, plate I.) Each of these tissues is composed of hollow, boxlike units called cells, and the cells of each tissue differ from those of the others in structure, form, and composition, so that each tissue differs widely from any other in structure, composition, and general nature. Besides, many of the cells include within their walls a number of waste products, such as resins, terpenes, tannins, fats, oils, alcohols, waxes, and a number of pigment or coloring matters. These cell contents are of great importance in coal formation.

The Pith

The pith, p, (figs. 7 and 12, plate I), forms the central part of the stem, roughly in the form of a thin cylinder. Its cells are thin-walled, composed of cellulose; in some cases, however, they are lignified. In certain conifers they include considerable amounts of waste products.

3/ Editorial comment: Later studies have shown that certain Cretaceous and Tertiary coals of America were derived chiefly from nonconiferous vegetation.

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The Xylem

The wood or xylem, as shown in figures 7 through 12, plate I, surrounds the pith and is a far more important part. It consists of three kinds of cells: (1) long, tubelike, thick-walled, lignified cells with the long axis parallel to the sten, called tracheids or wood fibers. and forming the bulk of the wood, tr; (2) more or less isodiametric, irregular thin-walled cells and forming resin ducts or reservoir, rd; (3) short box-like thin-walled cells arranged in bands at right angles to the fibers or tracheids and radiating from the center, called rays or medullary rays, ra. These very often include resins.

The wood, w (figs. 7 and 12, plate I), grows in thickness through the growth of a living tissue surrounding the wood, called the cambium, ca.

In order to study the xylem or wood more closely, it is necessary to cut thin sections in three directions - transversely, radially, and tangentially - each giving a picture totally different from the other. A diagrammatic illustration of these directions is shown in figure 8, plate I.

A transverse section of pine wood is shown in figure 9, plate I. Here, the tracheids, tr, cut crosswise annual rings, ar, each with the early and late wood, a resin duct, rd, and a ray, ra, consisting of short cells end to end and inclosing nuclei.

A radial section is shown in figure 10, plate I. In this the tracheids, tr, are cut longitudinally. The circular forms are the bordered pits, bp, which afford communication between the tracheids. Figure 11, plate I, shows a tangential section, in which the tracheids, tr, also are cut longitudinally. Bordered pits, bp, are found only on the radial walls and are here shown as small lenticular forms in the cell walls. This section also shows the ends of the rays, ra, consisting of from one to 12 cells one above the other.

The Bark

Bark is that part of the sten that surrounds the xylem or wood and forms the outermost part of the stem. In the young stem it consists of a number of tissues (as shown in figs. 7 and 12, plate I, and figs. 1 and 6, plate II): phloem, ph, pericycle, endoderm, cortex, co, and epiderm, ep.

The phloem is probably the most interesting and most important tissue of any conifer and also the most complex. It will be remembered that the wood owes its annual increment to the growth of the cambium, ca. As the cambium adds each year to the wood, so also the cambium adds outwardly to the phloem throughout the life of the tree.

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PLATE II

Fig. 1. Part of transverse section of a 2-year-old shoot of the bald cypress. w - wood; ca - cambium; ph - phloem with accummulations of dark-colored substances in the waste reservoirs; dph - dead phloem and dead cork tissues taking the place of the original epidermal tissues. X100.

Fig. 2. A more highly magnified portion of the phloem. fi - fibers; st - sieve-tubes; wr - waste reservoirs filled with waste matter; others are still empty of waste matters; re - medullary ray. X500.

Fig. 3. Radial section of a young shoot of the bald cypress. w - wood; ph - phloem; dph - dead phloem and cork tissues; ra - medullary ray. X50.

Fig. 4. Radial section of the same at a high magnification. fi - fibers; st - sieve-tubes; wr - waste reservoirs, some filled with waste matter. X250.

Fig. 5. Cross section of the needle of a spruce, the ordinary Christmas tree. lp - leaf parenchyma; ed - endoderm; vb - vascular bundle; hy - hypoderm; cu - cuticle; rd - resin ducts or reservoirs. About X25.

Fig. 6. Transverse section of part of a young pine shoot. co - cortex; phn - phellogen; hy - hypoderm; cu - cuticle.

Fig. 7. Herbarium specimens of Lycopodium obscurum, or common ground pine or club moss, with cones.

Fig. 8. One of the cones enlarged, showing sporophylls.

Fig. 9. One of the sporophylls enlarged, showing sporangium underneath filled with spores.

Fig. 10. A number of the spores of the same plant. X100.

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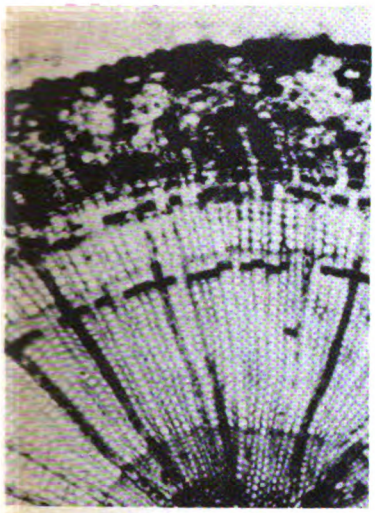

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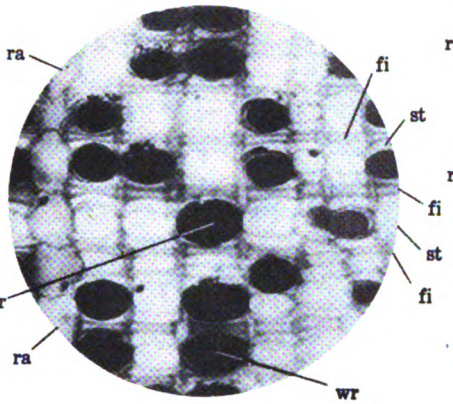

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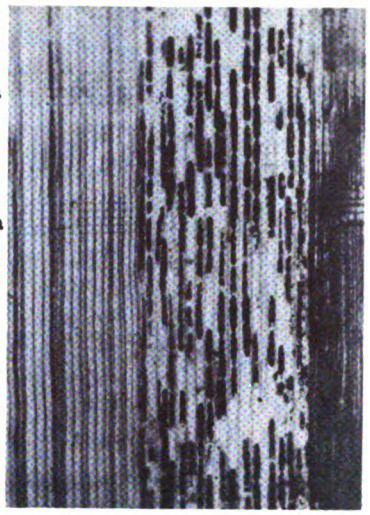

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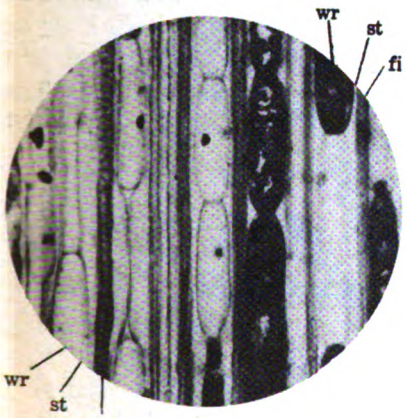

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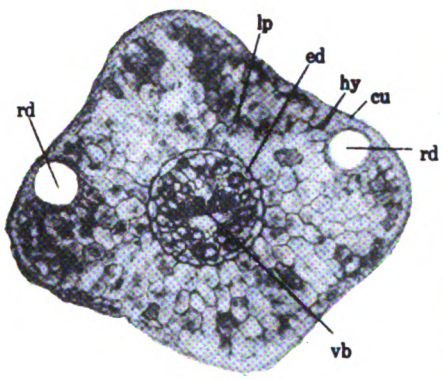

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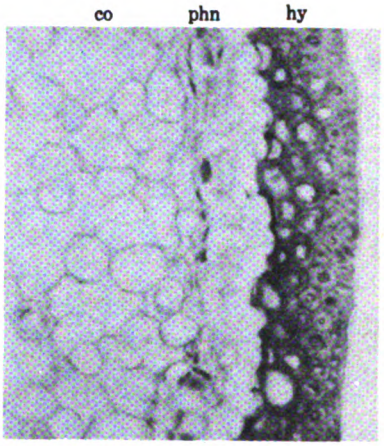

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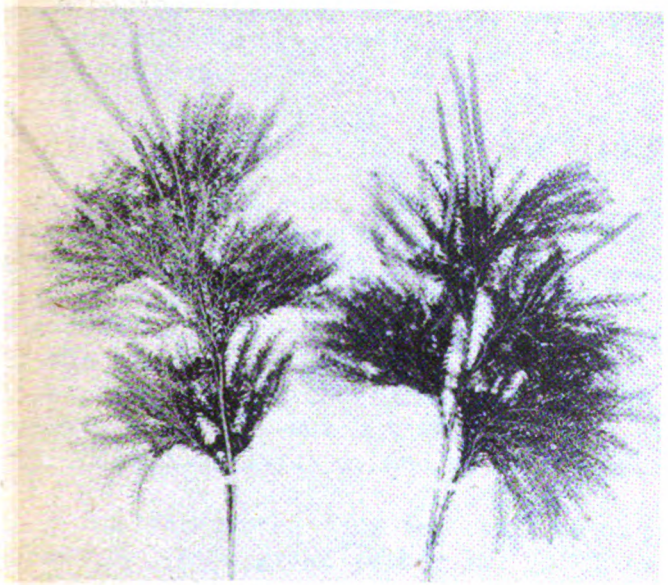

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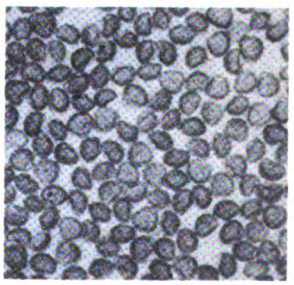

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Figure 12, plate I, and figure 1, plate II, represent the transverse section of a very young cypress shoot and show the relationship of the phloem cambium and wood, whereas figure 2, plate II, shows the structure of the phloem at a high magnification. As seen in transverse section, it consists (1) of rows of large, bulging cells, wr, the walls of which are composed of cellulose. A number of these are filled with a dark-brown granular substance, a waste matter; the cells are thus waste reservoirs. These large cells are (2) accompanied on each side by thin-walled cells bearing sieve plates, and are, therefore, sieve tubes, st. These three rows of cells, that is, reservoirs with a sieve tube on each side, are separated by rows of thick-walled lignified fibers, fi, in well-defined tangential rows. Radially, a number of these elements are arranged in radial wedges by means of the rays, ra.

In the longitudinal sections (figs. 3 and 4, plate II) the waste reservoirs, wr, are shown as long, bulging cells joined endwise by horizontal walls; some are shown to be filled with waste matter, whereas others are filled with cytoplasm. On each side are shown the long, thin-walled, tapering, and overlapping sieve tubes, st. Each trio (that is, waste cells with its sieve tubes) on each side is separated by the long, tapering, thick-walled, lignified fibers, fi. This general structure of phloem, with a few minor modifications, is characteristic of most living conifers.

The Cortex

Surrounding the phloem, but separated from it by the pericycle, which is of little importance, is the cortex, co (fig. 6, plate II). It is composed of a number of kinds of cells arranged in many different ways, often without any particular order. Most of the cells are parenchymatous, mixed with thick-walled, lignified fibers, and stone-cells either in the form of strands or nests. The walls of the parenchymatous cells are often impregnated with dark coloring matters, and the cells themselves contain chlorophyll, or green coloring matter of leaves, resins, mucilages, tannins, and other waste products. Further, the cortex contains various kinds of resin and gum ducts or reservoirs, rd, (fig. 7, plate I) filled with resinous waste matters.

The Epiderm

The outer tissues comprise the epiderm and consist of two parts - the hypoderm, hy, and the cuticle, cu. (Fig. 6, plate II.) The hypoderm consists of one to several layers of thick-walled schlerenchymatous cells forming a sheet with two kinds of openings called stomata and lenticles. The cuticle is a noncellular, hyaline membrane with openings corresponding to the stomata and lenticles forming the outermost covering of all young stems, shoots, leaves, barks, and scales. It is composed of cutin, waxes, resins, and oils, which together form a covering very resistant to weathering, chemical reagents, and micro-organisms.

The structures thus far considered pertain primarily to the young shoots or stems grown each year. At first sight, these may appear unimportant with respect to peat and coal formation; but when the enormous

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number of shoots grown and the enormous amount of substances they furnish every year and the enormous amount of waste products they contain are considered, the importance becomes significant. Further, when it is considered that the epiderm and the cortex of the young shoot of the conifers are only short-lived and are soon thrown off, their importance becomes doubly significant.

Soon after the primary cortex, with its enveloping epiderm, is fully developed, there is formed in the cortex, just below the epiderm, a new generative layer (fig. 6, plate II) called the phellogen, phn. Its cells divide tangentially and give rise to a layer of cork only in some conifers and to a layer of cork toward the outside and a layer of cortex to the inside in others, forming a sheath around the young shoot.

Soon other generative layers are formed deeper in the primary cortex either as complete circles or arcs and chords. These layers of cork cut off the outer part from the inner living tissue, which then dies. As the shoot grows, this phellogen cuts in deeper and deeper, finally cutting off the cortex altogether, and continuing to cut into the phloem. The outer parts cut off invariably die and either accumulate as dead bark or are sloughed off as dead bark. (Fig. 12, plate I, and fig. 1, plate II.)

It can readily be seen that the epiderm and the cortex sloughed off contribute a considerable mass of plant matter to the deposit, considering the enormous number of young shoots grown every year.

The Leaves or Needles of Conifers

The leaves or needles of conifers are important organs in peat formation. Owing to their large amount of fibrous tissues, thick periderm, and particularly owing to the large amount of resinous matter contained as cell contents, they leave large proportions of this material in the form of fibrous and resinous peat. Figure 5, plate II, represents the cross-section of needle of the black spruce or common Christmas tree. In the center is a woody, vascular bundle surrounded by a cylindrical endoderm. Surrounding this is the leaf parenchyma, in which are seen two large resin ducts or resin reservoirs normally filled with resin. The parenchyma cells are crowded with resins, terpenes, tannins, and chlorophyll or green coloring matter. The whole is enclosed by a thick hypoderm covered by a thick cuticle. At the time when the needle is shed, it is crowded still more with waste matters. Owing to their resinous nature, coniferous needles are very highly inflammable.

Spores

Remains of spores are ever-present constituents in all coals. They are easily seen because of their clear yellow color and transparency and thus are the most obvious objects. The remains of spores in coal consist merely of the outermost shells, called the exines or spores.

The easiest way to explain what spores or spore-exines are is to refer to the ordinary ferns so often grown in pots as house plants. On the under

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side of the leaves, rows of dots can be seen at almost any time of the year. At certain times when the leaves are handled, a fine dust comes off. This dust consists of the spores of the fern. Such spores are the asexual reproductive organs, not only in the fern but of all the lower plants, such as liverworts, mosses, horsetails, and lycopods. The ancient lepidodendrons and sigillaria belonged to the lycopods.

A better example to illustrate the origin of spores in coal is the common clubmoss, or ground pine, one of the lycopods, whose ancestors, the lepidodendrons and sigillaria, contributed largely to coal. The clubmosses or ground pines are small treelike or bushy plants hardly more than a foot high (fig. 7, plate II), although their ancestors grew to be large trees.

The stems and branches are clothed with small, scalelike leaves. Some of the erect branches are terminated by conspicuous cones. These cones have the appearance of clubs and from these and their mosslike appearance are called clubmosses. The cones (fig. 8, plate II) consist of closely overlapping scalelike leaves called sporophylls. On the underside of each of these is a globular sack (fig. 9, plate II) called a sporangium. Each sporangium is filled with thousands of spores (fig. 10; plate II). It is the source of the lycopodium powder for sale in drugstores and used for various purposes.

The spores in these plants are all of the same size and are called isospores. In some of the lycopodias, as in selaginella, here only grown in greenhouses, there are two kinds of spores. The spores in the upper part of the cones are all small; that is, they are microspores, whereas those in the lower part of the cones are much larger and are megaspores.

These microscopic spherical bodies consist of an inner living or cytoplasmic part surrounded by a thin membrane, the intine. The whole is enclosed in a much thicker shell, called the exine. This outer shell is composed of a number of substances, such as cellulose, sporonin, resins, oils, and waxes, which together form a covering very resistant to weathering, chemical reagents, and micro-organisms. During the peat stage, the living parts decay easily and contribute nothing or but very little to the deposit. Whereas the outer coatings or exines withstand all the peat-forming and coal-forming processes and remain well-preserved and so form appreciable constituents in all coals.

The Composition of Conifers

It is further of the utmost importance to know something about the chemical composition of the peat- and coal-forming plants.

Again, only a hurried survey is possible. References have been made to a number of products and chemical compositions; these must be further elucidated.

Green plants manufacture their own foods from water and carbon dioxide. Water is drawn up by the roots and transferred through the vascular tissues of the stem and branches into the leaves. The carbon dioxide is taken in

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by the leaves, through the stomata or leaf pores, into the leaf tissues. Through the energy of sunlight and by the aid of the green coloring matter or chlorophyll of the leaves, water and carbon dioxide are converted into plant foods. This process is called photosynthesis, the only means to provide food for all living things on earth. Some biochemists believe that the first product is formaldehyde. This may be condensed to glucose or grape sugar, from which, in turn, cane sugar, starch, and cellulose are formed. From the sugars and starch, with the addition of nitrogen and sulfur, all other plant substances are then formed by the living processes of the plant, either through building up or assimilation or tearing down or disassimilation processes.

The products formed by plants, and of which they are composed, are fairly well known and can be definitely outlined as follows:

A. Carbohydrates:

1. Simple sugars, like glucose or grape sugar, mannose and fructose.
2. Cane sugar, the ordinary white sugar, and starch.
3. Cellulose } Cellulose and lignin together form
4. Lignin } wood and other lignified tissues.
5. Hemicelluloses
6. Pectin - the substance that makes preserves jellify. Certo is largely pectin.
7. Gum - the jellylike substance that oozes from the bark of cherry trees is a gum.

B. Glucosides. The bitter substances in the bark of the willow and poplar are glucosides.

C. Tannins. The substance tanners use to make leather out of hide.

D. Pigments:

1. Chlorophyll, or green coloring matter in leaves.
2. Carotinoids - yellow coloring matters, such as in the carrot.
3. Anthocyans - coloring matter such as in flowers.

E. Acids and their salts:
1. Fats, oils, waxes.
2. Lipoids.

F. Essential oils:
1. Terpenes.
2. Camphors.

G. Resins.

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H. Vegetable bases or nitrogenous compounds:

1. Amines.
2. Alkaloids.
3. Purenes.
4. Nuclei acids.

I. Proteins.

J. Enzymes.

The total number of compounds is very large and it takes volumes to describe them all, but the more common members must be discussed briefly.

Cellulose

Cellulose is a white hygroscopic substance insoluble in water and most other solvents. In nature it is found in its purest form in cotton, flax, hemp, and sisal fibers. Filter paper is virtually pure cellulose.

Chemically, it is like, but not identical with, starch, sugar and glucose; in fact, it may be made to break down into glucose. When left to decay, as in stagnant water in swamps, etc., cellulose breaks down into carbon dioxide and marsh gas. The bubbles that come up through the water in marshes are marsh gas and carbon dioxide. Marsh gas is the same as methane or natural gas. The air exhaled from our lungs contains carbon dioxide.

The cell walls of the growing tissues of young plants consist of virtually pure cellulose; but as the tissues grow older, they become impregnated with lignin and hemicelluloses, as in wood. The tissue or cell wall is then said to be lignified.

Lignin

This brings up the question as to what is lignin. In spite of the large amount of research work done on lignin, it is today impossible to define it precisely. Considering all the results obtained through investigations, it must be concluded that it has not been proven that it is or is not a unit substance, and cannot be expressed by a formula. All that can safely be said about it is that it is something associated in some way with cellulose to form the so-called ligno-cellulose in wood and other lignified tissues.

Lignin is attacked but slowly by bacteria and fungi. Most fungi do not attack it when lignin is inoculated with them. A few fungi, however, are known that will attack lignin in wood but not the cellulose, causing the so-called white rot.

The amounts of lignin and cellulose obtained from wood vary widely in the different woods, in different ages of wood, whether sapwood or heartwood, whether of a conifer or a leafy tree. In round numbers the amount of

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cellulose in wood is from 45 to 60 percent and lignin from 22 to 35 percent, the remainder being chiefly hemicelluloses and moisture.

Hemicelluloses

The hemicelluloses include a series of complex sugars. They occur in the cell walls of wood fibers, in the cell walls of seeds of various plants, in the shells of nuts, stones of fruits, seed coats of beans and peas, and, in fact, in most tissues in small quantities. They are much more easily decomposed than the cellulose and when hydrolyzed yield chiefly galactose, mannose, and pentoses, similarly as starch and cellulose yield glucose.

Functional Classes of Plant Substances

Plant substances may also be grouped according to their role in plant life. Those serving -

As framework, such as wood, fibers, and bark;
In the living processes, as cytoplasm or protoplasm;
As reserves and foods, as sugar, starch and fats;
As protective agencies such as cuticles, cork, and hairs;
And as waste matter, as resin, gums, etc.

The wood, bark fibers, schlerenchymatous tissues in the bark or cortex, and epidermal tissues provide the framework and supporting tissues and constitute the bulk of the plant.

The living substances include protoplasm or cytoplasm and enzymes. They are the essential substances for the plant's life and growth.

Reserve and food substances accumulate in various tissues and are available for the plant itself or its seeds for future use. Sugars, starches, fat, oils, and proteins may serve as reserve foods.

Waste substances are those thrown off by the plant as a result of life processes and are deposited in various cells, cavities, ducts, etc., and are of no further use as foods, and are not readily decomposed by micro-organisms. To these belong the resins, camphors, terpenes, glucosides, alkaloids, tannins, and oxidized tannins.

Protective substances, as the name implies, serve to protect the plant from exterior forces and injuries such as, weather, heat, cold, moisture, drought, and living organisms. Under these are to be classed fats, oils, waxes, resins, sporonin, pollenin, cutin, and suberin. They form the coverings of the leaves, stems, and fruit mainly in the form of cuticles, cork, hair, spore exines, and pollen exines.

The Decomposition Processes

A little discussion must be devoted to the rotting of the plant material in the process of peat formation. The actions of micro-organisms on the

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plant matter are probably the most important factors in peat formation and, therefore, also in the formation of coal.

Immediately after the death of a plant, when those functions about which so little is known and which protect the plant from the attack of micro-organisms cease to exist, it becomes a host of fungi actinomyces and bacteria. These organisms make their living on the plant substances, but in order to do this they must first dissolve or decompose them. The dissolved substances are then absorbed into the organisms. This process is called fermentation and, in plain language, is rotting. As long as the plant matter remains in the air and in a moist condition, rotting proceeds rapidly; but when the matter is covered up by the subsequent debris and submerged by water and deprived of the free access of air, rotting proceeds very slowly.

Variable Resistivity

Plant substances vary greatly with respect to resistance to rotting or decay. Some substances are attacked and rot readily; others rot much more slowly or not at all. Those substances that comprised the living parts and those that served as foods, such as protoplasm, proteins, sugars, and starch, are attacked readily and decompose easily and quickly, and very little or nothing remains of them when exposed under favorable conditions. Components of the cell walls are slightly more resistant, but the different components of the cell wall, such as cellulose, lignin, and hemicelluloses, among themselves vary considerably in the ease with which they are decomposed. The hemicelluloses decompose more readily than cellulose, whereas lignin is far more resistant than cellulose. When wood or woody tissues are left in favorable conditions, the celluloses are almost completely decomposed within a few years, whereas the lignin largely remains in an altered condition known as humins. The protective substances and tissues, such as cuticles, spore walls, and pollen walls, are scarcely attacked at all. The waste products, such as the resins, terpenes, camphors, waxes, higher alcohols, fats, and oils are also decomposed but little or not at all.

Because certain plant products, tissues, and organs are present, perhaps, in only small amounts but decompose with difficulty or not at all, and although other products, tissues, and organs that constitute the larger part of the plant decompose more easily and disappear to a large extent or completely, the former are concentrated and remain in the debris in proportions many times larger than in the plant originally. Therefore, at all times the more easily decomposable substances are being eliminated and the more and most resistant are being concentrated.

It is also known that the wood of certain species of trees is more easily decomposed than that of others. The wood of the tamarack, for example, rots more readily than the spruce, and the spruce more readily than the white cedar. In the same swamp, under the same conditions, the wood of the tamarack may be reduced to debris whereas that of the cedar may still be solid. Some woods and some tissues and organs contain more toxic substances than others; the resinous substances, in particular, are good preservers, and plants containing them are therefore more resistant to decay than others.

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PLATE III

Fig. 1. A lump of dried peat including a number of chips of peatified wood.

Fig. 2. Chips and fragments of peatified wood from a similar lump of peat separated from the finer debris.

Fig. 3. Some of the fine debris of a lump of peat magnified to show the remaining plant structures. About X25.

Fig. 4. Some of the fine debris at a higher magnification, showing plant structure and cell contents. X100.

Fig. 5. Thin transverse section of one of the peatified wood fragments in a medium state of decomposition, with four annual growth rings. X100.

Fig. 6. Part of the early wood of the same section at a high magnification, showing the thinned and ragged appearance of the wood fibers and the dark secondary zones. X500.

Fig. 7. Part of the late wood of the same section, at a high magnification, showing the ragged nature of the wood fibers, and in particular the darkened secondary zones. X500.

Fig. 8. Thin transverse section of peatified wood in an advanced state of decomposition. X100.

Fig. 9. Thin tangential section of peatified wood in an advanced state of decomposition. Resin-filled medullary rays are seen in cross section of the tangential surface. X100.

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Plate III

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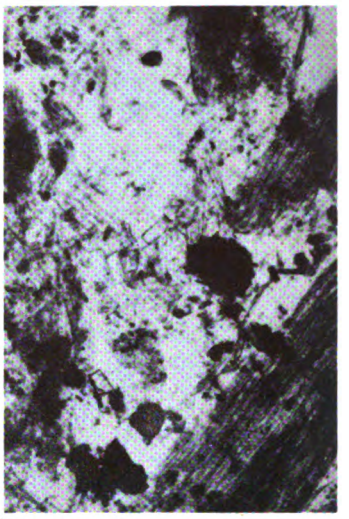

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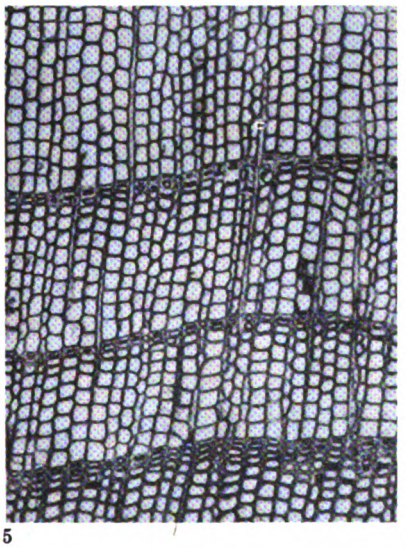

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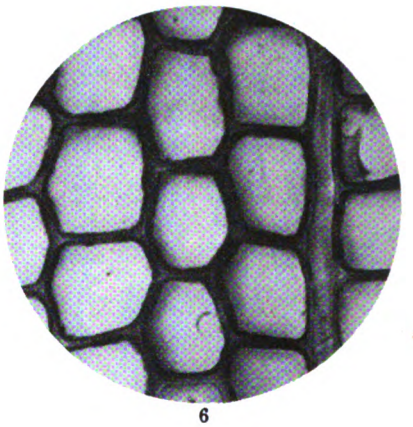

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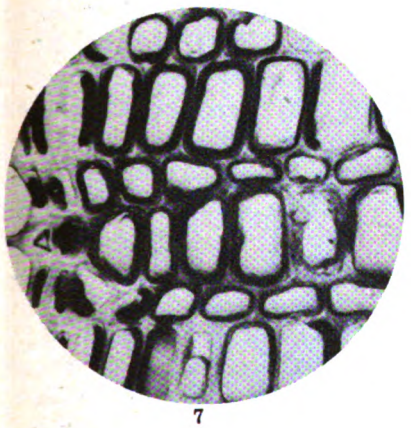

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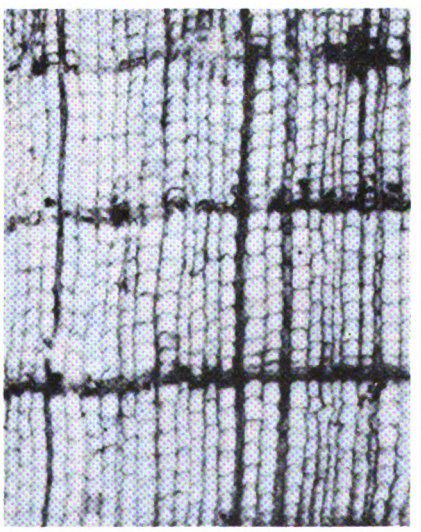

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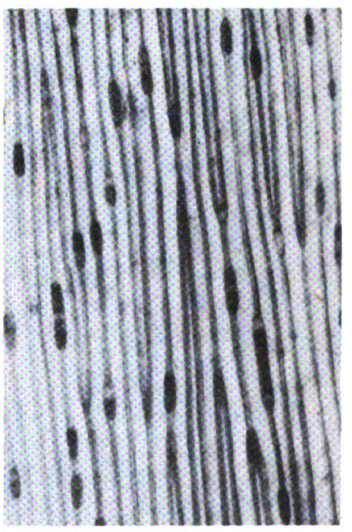

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Further, a number of stems or trunks are buried while still alive and by the time they have died are covered by a fairly thick layer of debris and are submerged below the water level, in which fungi cannot exist. Bacteria alone will not attack sound wood, or only very slowly, and do not penetrate it to any depth. Such material is not disintegrated further than at the time of submersion. In the long run, however, it is probably hydrolyzed through acids of the peat water and the products further decomposed by micro-organisms.

To recapitulate briefly, we see that every year during the growing seasons the peat floras grow new leaves, shoots, flowers, seeds, bracts, pollens, and spores; wood and bark are added to the stems, twigs and roots; waste products, gums, resins, terpenes, and tannins are stored in cells, ducts, and reservoirs. On the other hand, leaves, petioles, bracts, pollens, and spores are shed at the end of the season; large proportions of the young shoots and dead twigs are dropped; part of the old bark is peeled off; finally, twigs, branches, and whole trees are broken down by wind, rain, and ice; some trees always die through one sort of injury or another and eventually fall, and all are added to the accumulating debris. Other trees, owing to lack of proper hold on the loose substratum, gradually lean over more and more and finally, while still alive, are buried alive by the debris dropped year after year. Thus, an equilibrium is maintained between growth and drop. Micro-organisms, small animal life, wind, and weather bring about decomposition, maceration, elimination, and concentration. Thus, there is an ever-accumulating mass in all stages of decomposition, maceration, elimination, and concentration of matter called peat.

THE COMPOSITION OF PEAT

We must now look closer into the composition of peat; what parts, what products, and what tissues of the plant have remained, and what now is their nature and appearance in the form of peat. A lump of peat may be removed from the more mature depths of the deposit without disturbing its natural deposition and examined, first with the unaided eye, as to its outward appearances and for the visible and recognizable components. Figure 1, plate III, represents such a lump in a dried condition. Immediately after its removal from the bog it looked more like a lump of mud, but in the dried condition it is similar to brown coal. Conspicuous are a number of chips of wood turned into peat, of greatly varying sizes and forms, all imbedded in more finely macerated debris or attrital matter. On close inspection there seems to be no division in size between the largest and the smallest constituent in the lump. It must also be remembered that the lump does not include any of the larger fragments of woody peat, of which there are a considerable number, consisting of large parts of stems or trunks.

Separation of the Finer and Coarser Components

A similar lump fresh from the bog may be separated by agitation in water into the coarser components and a finer debris. A separation of the coarser material is shown in figure 2, plate III. The fragments are all of coniferous wood; some consist of flat chips, others are split fragments of stems, and others are rounded fragments of stems or roots. All sizes and many forms are represented.

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The Finer Debris

The finer debris separated from the larger constituents, as seen in a lump, looks very much like ordinary black mud, but even when examined only under a hand lens much of it is revealed to consist of macerated plant parts with structure well preserved. When examined at higher magnifications, it is seen that all consists of macerated plant tissues, organs, and fragments of cells (figs. 3 and 4, plate III). Further examination reveals that it is derived from all conceivable tissues of the plants growing in the swamp. Wood, bark, and leaves are all represented. The most important fact learned is that the more resistant tissues, in particular the cell contents, have remained and have been highly concentrated and now form a large part. (Fig. 4, plate III.)

While the examination of peat in a dispersed form under the microscope is of the greatest importance in the recognition and identification of the various constituents, it affords a poor means of comparing it directly with coal, and later we shall have to examine it in a compressed peat briquette in thin sections, and compare its constituents directly with those in thin coal sections.

THE MICROSTRUCTURE OF PEAT-WOOD IN ITS NATURAL CONDITION

We must now go back and look more closely at the woody material remaining in peat and see what has happened to it through rotting or, in other words, the process of peat formation. This is of the greatest importance to an understanding of the true nature of coal.

We shall have to resort to cutting thin sections of the woody fragments and examining them under the microscope. The appearance and condition of the thin sections depend largely upon the degree of decomposition, or rotting, and alteration. As has been intimated, the components of peat are found to be in greatly varying degrees of decomposition, ranging from only slight alteration, in which only a small part of the cellulose has been lost, to such that all, or almost all, of the cellulose has disappeared, leaving nothing but the lignin in a much altered state. Such differences may exist even in one and the same fragment. Most of the material, however, is in an advanced state of decomposition. In figure 5, plate III, is represented a thin transverse section of peaty wood of a white cedar in a semirotted contition but with a fairly well preserved structure, and which has retained a small amount of cellulose. The walls of the wood fibers or tracheids have (although not much thinner than in the sound state) assumed a ragged, mushy appearance as compared with a similar section of sound pine wood. (Fig. 9, plate I.) This is much better shown in higher magnification. Figure 6, plate III, represents part of the same section from the summer wood at a high magnification and in which the ragged nature of the cross section of the fibers is quite noticeable. Particular attention is called to the dark lining of the inside of the fibers. Figure 7, plate III, represents a part of the late wood. It will be noticed that the walls of the fibers of the late wood are much thicker than those of the summer wood, and that the preservation of the former is much better than that of the latter, a condition that always holds true wherever

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annual growth rings have been formed. Nevertheless, it is clearly seen that they have lost much of their solidity and firmness. Here it is again shown that the broad inner zones or the secondary zones of the walls have also assumed a very dark color. This is a very important feature in coal formation, to which we shall have occasion to refer later.

Figure 8, plate III, represents a transverse section of another fragment of coniferous wood in a more advanced state of decomposition. The fluffy and loose structure of the fiber walls is well shown.

For the sake of comparison and recognition of similar structures in coal, a tangential section of coniferous woody peat must also be presented, because sections of similar structures are frequently found in coal. Figure 9, plate III, represents such a section. In this are recognized (1) the wood fibers in longitudinal sections, (2) the cross section of bordered pits in a number of two adjoining walls, and (3) the rays, seen in cross section, filled with resins.

The fiber walls of such a piece of woody peat are in a colloidal state; that is, the walls are built up of very small particles called micelles. These micelles can be made clearly visible by proper microscopic means.

MICROSTRUCTURE OF PEAT-WOOD IN THE COMPRESSED CONDITION

Although the knowledge of the microstructure of peat-wood in its natural uncompressed condition is of great value in getting a correct idea as to the origin of coal, it does not afford a fair comparison of it with the structure of coal. When peat is compressed under high pressure into a briquette, it becomes similar to coal, and direct comparisons may be made. Peat briquettes made under high pressure during a long time assume much the appearance of lignite and are amenable to thin sectioning. The thin sections of such a briquette have very much the same appearance as those of a brown coal and lignite and in some cases are indistinguishable from them. Having learned from a study of the peat mass as to what it actually consists of, it is not difficult to identify and correlate the various constituents in peat in a thin section prepared from a briquette, and correlate them directly with those seen in thin sections of brown coal, of lignite, and of all the coals of higher rank.

The appearance of thin sections of peat wood in a compressed condition is wholly different from that of peat wood in the natural or uncompressed state, and the inexperienced observer would not know that they were the same. The following illustrations will give a much better idea of the nature of compressed peat than any description could render.

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PLATE IV

Fig. 1. Transverse section of compressed peatified wood in an advanced state of decomposition. This illustration is to be compared with the uncompressed peatified wood illustrated in plate III, figures 5-8. X100.

Fig. 2. Transverse section of part of the same section at a high magnification, showing the structure and mode of collapse in detail. X500.

Fig. 3. Thin section of compressed peat, consisting of a part of a longitudinal section of a young twig or shoot with the wood and bark intact. The bark has been highly disorganized and now consists largely of the remains of cell contents with a small part of the dark brown tissues remaining. The wood also is much disorganized. X100.

Fig. 4. Transverse section of a fragment of peatified phloem at a high magnification.. X500.

Fig. 5. Thin section of compressed peat; a general attritus enclosing a small stem or twig with wood and bark intact. X100.

Fig. 6. A small part of the general attritus at a high magnification, consisting of a resinous debris including tissue fragments. X500.

Fig. 7. Thin section of a portion of attrital matter of compressed peat at a high magnification, the remains of a cortex. The cell walls have been reduced greatly, whereas their cell contents have retained their original bulk. X500.

Fig. 8. A block of Pittsburgh coal, illustrating the general striations or layering of coal into black, glossy, and grayish attrital bands. 1/2 natural size.

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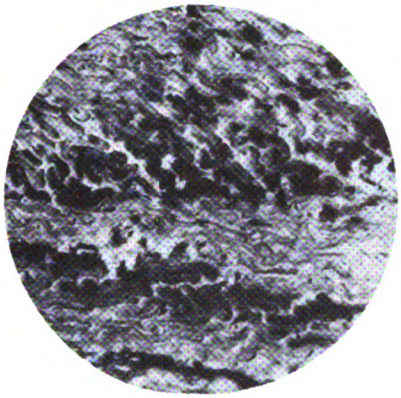
Plate IV

1



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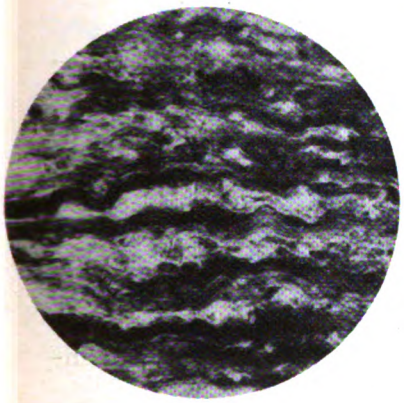

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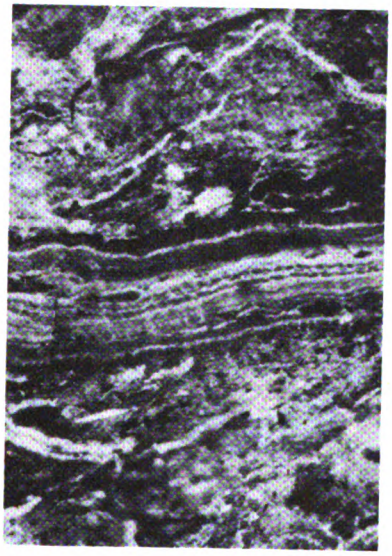

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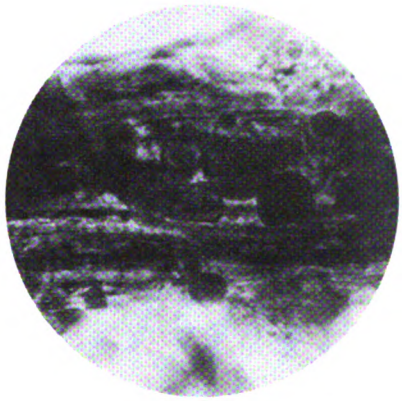

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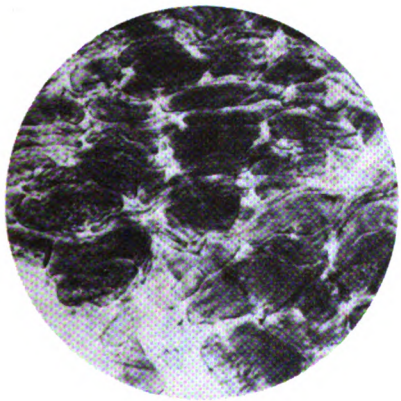

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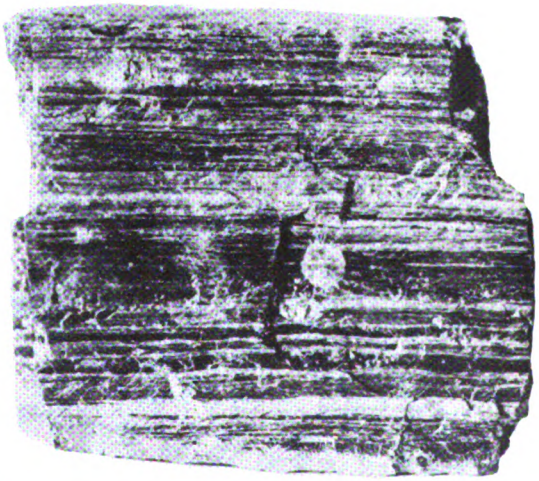

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Figure 1, plate IV, represents the thin transverse section of coniferous peat wood embedded in a highly compressed peat briquette, and figure 2, plate IV, represents a part of the same figure at a high magnification. The wood was in an advanced state of decomposition, the early wood being reduced to irregular black zones. Although the cell walls of uncompressed peat wood are fully distended, just as in sound wood, in the compressed condition they have been pressed together and the open spaces have completely disappeared.

Figure 3, plate IV, represents a thin longitudinal section of a coniferous twiglet in a compressed briquette, with the bark and wood intact, at a magnification of 100 diameters. The wood fibers have been pressed closely together, and the resins are concentrated. In the bark, the dark-brown cell walls with their dark-brown contents have been compressed so that they now appear as opaque masses. At a close examination of the thin section the various elements are still discernable. The phloem has suffered most.

OLD PHLOEM IN PEAT

Fragments of old phloem, or phloem from the outer bark, form numerous though inconspicuous constituents in peat. As seen under the microscope, it consists of alternate dark and light layers. Figure 4, plate IV, shows the characteristic appearance and should be compared with the old phloem of the bald cypress (fig. 3, plate II). The lighter zones are the remains of the fibers, and the dark zones are the remains of the sieve tubes and the waste reservoirs. The cell walls of the latter two, being originally composed of cellulose, have suffered the greatest loss and are lost among the dark-colored remains of the contents of waste reservoirs and the originally thick-walled lignified fibers, now also much distorted and crushed. This phloem is probably that of the white cedar, the predominant contributor to the peat.

These illustrations are a few of the very many examples observed in thin section, in which the various tissues, with their characteristic cells and cell contents, are clearly identifiable without a doubt. These then serve as patterns or criteria for the recognition of isolated tissues or groups of cells, or even single cells in the attritus, not only applicable to peat, but also to coals of higher rank.

THE ATTRITUS OF COMPRESSED PEAT

In the study of thin sections of the attritus of compressed peat, valuable information is obtained with respect to the distribution of the various constituents, their relative frequency, and their general appearance for further comparison with those of coals of higher rank.

The various constituents found in the attritus have been recounted in the study of peat in its natural state, and we have become familiar with them as they exist in the natural or uncompressed condition. From this and the knowledge of the plant tissues, they may now be identified in thin sections of compressed peat.

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A thin section of compressed peat is of a yellowish, dark-red to dark-brown color, quite similar to that of brown coal and lignite. Under the microscope, at a magnification of 200 or more diameters, the various constituents may be distinguished readily. In a photomicrograph of a magnification of 200 diameters this is not so clearly done, owing to the similarity of color and texture and to the thickness of the section; but at a magnification of 1,000 diameters, the differentiation is clearer and the different constituents stand out more sharply.

Figure 5, plate IV, is a section of the attritus of average composition and encloses a fragment of a small stem cut in an approximately longitudinal direction with all the tissues intact and discernable but highly compressed. Degradation matter of cedar leaves forms an appreciable part of the attritus.

At a higher magnification, it may readily be seen that the attrital matter of peat consists of numerous very small fragments or bits of tissue of all kinds, such as wood, phloem, cortex, cork, periderm, and free resin particles separated from the tissues. The following are a few random illustrations out of innumerable examples that could be reproduced.

Figure 6, plate IV, represents the remains of thick-walled, lignified hypodermal tissues lodged in a highly decomposed, resinous debris. Figure 7, plate IV, represents a fragment of cortex composed of cells, the walls of which have become very thin, but filled with a resinous brown matter.

These few illustrations, which could be duplicated many times, should be enough to give a general idea of the composition of peat and the origin of its constituents.

In review, a number of general but important facts may be pointed out. All light-colored tissues, cells, fibers, and stone cells of the contributing plant gave rise, in general, to more light-colored constituents in peat; all stained or brown tissues, cells, and fibers gave rise to dark-colored constituents. As the outer bark is largely composed of dark-colored tissues and is, in general, of a dark-brown color, it gives rise to brown-colored constituents in peat. Cells and tissues composed only of cellulose have decomposed most, although remains of such cells and tissues, in large numbers are recognized. Wood parenchyma, rays, phloem rays, sieve tubes, and pericycle in general are decomposed and lost to a larger degree than any other tissues, often leaving but a trace; in some cases, however, a considerable amount has remained. Lignified tissues and lignified cells have, in general, survived to a far larger, though varying, degree. Tracheids, bark fibers and stone cells, therefore, usually form a large part of the tissues remaining as peat. Cell walls, whether lignified or not, impregnated with brown coloring matter also have resisted decomposition to a large degree and also constitute a large part of certain remains of tissues. Cell contents of all kinds have resisted decomposition the most, and, in many cases, represent by far the larger part of remaining tissues, the once enclosing cell walls having largely and in some cases almost completely disappeared. Cell

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contents are classed as resins, resin-tannis, gums, waxes, oxidized substances, or phlobophenes, etc., but it is difficult to determine which was the most resistant. Many of these are probably present as mixtures.

The foregoing account of the origin and composition of peat reveals from which tissue or plant product each constituent was derived; it shows many of the changes with respect to structure and maceration. It also shows that many chemical changes have taken place, but as to what these chemical changes were and what the chemical natures of the remains are, very little is known, and they remain a fertile field for research.

THE TRANSFORMATION OF PEAT INTO COAL

We have now discussed the formation of peat at some length and should have some knowledge of its origin and composition. Although peat is not coal, it may be said that peat formation is analogous to coal formation and that it is its first stage of formation, and that coal was once in the form of peat, yet it requires to be shown how peat was transformed into coal.

The consensus of opinion among geologists is that coal beds were formed during a period of subsidence of the locality in which formed. This opinion is in accordance with petrographic observations made on coal deposits in general. Let us now imagine for a moment that the area of Wisconsin in which the peat bogs are located was gradually sinking, and sinking faster than the peat deposited in it could accumulate. It would then be transformed into a lake. In time, the peat deposit would be covered by the clays, sands, and silt washed in from the higher grounds surrounding it. In the Dismal Swamp of Virginia and South Carolina, we have such an example, which serves as a very good illustration. The area of Dismal Swamp is slowly being inundated. Not so very long ago the whole tract was swamp; today a lake (Lake Drummond) occupies a large area in the center. Towards the center of the lake, a number of stumps of bald cypresses appearing above water remain. Towards the shore, trees with more and more living branches remain, giving vivid evidence that the area was once covered with bald cypresses such as now form the predominant growth of Dismal Swamp. If not interfered with by artificial means in time to come, Dismal Swamp will have been transformed into a shallow lake - a larger Lake Drummond; in a still distant future, the silts, sands, and clays of the higher surrounding land will have filled in the lake and buried the peat deposit of the former swamp completely; and, again, after a greater lapse of time, the area may again be raised to higher levels and the peat would then show up as brown coal or coal of some higher rank.

Again, we have in a brown coal of the Pleistocene of King County, Washington, a very fine illustration; hundreds of thousands of years ago, a short time before the cycles of Ice Ages (a period called the Pleistocene in the earth's history), a deposit of ancient peat was formed and was later submerged and covered with a layer of sands, silts, and clays to a depth of approximately 125 feet, now partially changed into hard rock through cementation. This deposit of plant remains is now in an advanced state of peat, approaching the state called brown coal.

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The transformation of the peat or potential coal-forming material into brown coal may be said to have occurred in the following manner: After the deposit had been laid down, it was covered with the potential rock-forming material and, as time advanced, was elevated to the present position. During that time, the water was gradually withdrawn, the peat was gradually compacted, and certain chemical and physical changes took place, which resulted not only in loss of moisture but also in loss of oxygen and volatile matter and a relative increase in both fixed and total carbon up to a point that puts the material into that rank of coals called brown coal. This change or transformation of a peat or coal into a higher rank is called metamorphism or coalification.

Composition of the Pleistocene Brown Coal

Careful investigation reveals that this brown coal was formed from plant growth similar to that which formed the Wisconsin peats, and in a similar manner. Thin sections of this coal resembled those made from briquetted peat of Wisconsin so closely that certain sections could not be distinguished from others. On the whole, however, the plant material remaining in the brown coal is a slightly better state of preservation than that in the Wisconsin peat studied. Illustrations of the structure and the constituents forming it would merely duplicate the illustrations shown for peat.

The origin of this Pleistocene brown coal was in all probability very similar to that of the peats of Wisconsin and the peats of Dismal Swamp. In each of them the predominating plants were certain conifers, and if the Pleistocene Swamp could be restored, it would probably closely resemble either the Wisconsin or Dismal Swamp.

Older Deposits

The Pleistocene brown coal may be considered the second step in coal formation. From the Pleistocene, we may go back, step by step, to other periods in the earth's history in which coals were formed - first, to the coal in the Pliocene, then in higher rank in the Miocene, next in the Oligocene, and finally in the Eocene, all of Germany.

All of these deposits have but a light overburden, and none has advanced beyond the brown-coal state, although farther advanced than those of our Pleistocene. The identifiable plant remains are predominantly coniferous. The structure of these coals, although more diversified, is again similar to that of the peats and our brown coal.

The lower Eocene and the Upper Cretaceous provide us with the next step. In this period we find the typical lignites, as in Texas and Arkansas in the South and North Dakota in the West. These coals have a thick overburden consolidated into typical rock. Although the time is the same as that of the German brown coals, due to deeper burial and hence greater pressure and slightly higher temperatures these deposits have been coalified to that stage or rank called lignite.

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An interesting fact is that, again, the origin of these coals is similar to that of the brown coals under consideration, and that, again, a presentation of their structures and remains of plant constituents would, to a large extent, be a repetition of what has already been shown for the peats. The great difference in these, however, is the marked increase in coalification expressed through a greater compression, density, compactness, lower volatile matter and higher carbon content.

MOUNTAIN BUILDING AND EARTH MOVEMENT AS A CAUSE OF COALIFICATION

We have, in the Western States, good evidence of coalification through mountain-building and earth disturbances. In the eastern border of the Eocene and Cretaceous coal fields, as in North Dakota, as already stated, the coal has been coalified to the rank of lignites. As we go farther westward in the deposits of the same age and, in certain cases, in the same bed, and farther and farther into the mountainous region of Montana and Utah, the higher is the rank of the coal. First come the subbituminous coals, then the bituminous, and finally, in the most mountainous regions where upheaval has been greatest, the rank approaches an anthracite. The origin, structure, and remains of plant constituents are, in all cases, similar to those of the typical lignites. The change is a clear case of metamorphism.

THE PALEOZOIC COALS

The interval between the Cretaceous and the Carboniferous periods represents a long lapse of time, to be measured by millions of years. We still have to pass through the Jurassic, the Triassic, and into the Permian periods before we arrive at the main coal-bearing strata of the Paleozic era, and we may expect much to have happened in the way of changes in the plants that contributed to coal. The picture of the reconstructed swamp forest has changed markedly. (Fig. 1, plate VIII.) The conifers, however (the plants we have found to have been by far the most important contributors to all the younger coals, from the recent peats to the Cretaceous lignites and bituminous coals), have come through this vast span of time and geological history from the Paleozoic, in which they were also important contributors, with relatively small changes. To these must now be added, as important coal-forming trees, the lycopods and the cycadophytes. The calamites and sphenophylls appear to have been unimportant coal formers.

The conifers of Carboniferous times, therefore, require but little study beyond what is already known of the recent forms. The lycopods and the cycadophytes require some fundamental study in order to be able to identify their remains in the coals.

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During Paleozoic times, the conifers were represented by a considerable number of genera and species. The group as a whole is called Cordaitales.[4] The best-known genera are Poroxylon, Pitys, and Cordaites. Each of these, of course, is represented by a number of species. The best known of these is Cordaites, with a number of species. They were tall, slender trees (fig. 2, plate VIII) with trunks rising to a great height (as much as 90 feet) before branching and bearing at the top a dense crown composed of branches of various orders, on which simple leaves of large size grew in great abundance. The stems attained a diameter of several feet. The leaves were simple, elongated, and varied considerably in form in the different species. In some they reached a length of 3 feet or more and a width of 60 inches. The leaves were parallelly veined, much like those of Yucca or Zamia. In this respect these trees differed from most of our recent conifers. Yet some of our conifers of southern climates, like Agathis or the kauri pine of New Zealand, grown in some of our greenhouses, may be compared with some of the ancient cordaiteans with shorter leaves. The anatomical or microscopical structure also closely resembled that of the kauri pine. Although in outward appearances our well-known conifers, such as the pine, spruce, balsam, and hemlock, differ from the ancient conifers, some of our living conifers of southern climates resemble them both in the inner structure as well as in outward appearance. There is, therefore, an abundance of living material for comparison with their ancient remains.

THE OUTWARD OR MEGASCOPIC APPEARANCE OF COAL

Most coals have a laminated appearance as seen on the vertical cleavage fracture face. They are composed of sheets and layers of coal matter differing from one another in color, texture, gloss and fracture and varying greatly in width and length. (Fig. 8, plate IV.) In general, two kinds of materials are distinguishable, often standing in sharp contrast to each other, but sometimes quite indistinct in a natural fracture and sometimes merging imperceptibly into one another. The one is of a homogeneous, jet-black, often glossy appearance, is compact, breaking with a smooth often conchoidal fracture. The other is of a somewhat grayish, dull, more granular appearance, and breaks with a more irregular rough fracture. In some parts of a coal bed, the black glossy bands may form by far the larger part; in others, they may form but a small part, others have none or hardly any at all, as in the cannel. Between these extremes all possible proportions may exist. In some coals or part of the coal bed these bands may be relatively thick, in others of medium thinness, and in others very thin. In some they may be almost all relatively thin, as in the semisplint; in others, again, very thin and irregular, as in the splint but in every case, the dark, bright bands are embedded in the grayish part.

4/ Editorial comment: Although no distinction is made by Thiessen in this paper, most authors differentiate between Cordaitales and Coniferales. Some writers believe the cordaiteans are ancestral to more modern conifer groups. The most recent study of ancient conifers is by R. Florin: "Die Koniferen des Oberkarbons und des unteren Perms": Palaeontographica (Munich), vol. 85, Abteilung B (successive numbers) 1938-45.

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The Polished Surface

The general nature and layering of a coal are more evident in a polished vertical surface. (Fig. 1, plate V.) Most of the bands, it is seen at once, have a definite, sharp outline, although occasionally gradual transitions are observed. It is also definitely shown that there is a great variation in the thickness of the black bands without sharp demarkations from the thinnest to the thickest. It may again be shown that the grayish material is the embedding material for the black components, and that this is arranged quite generally in horizontal layering. Occasionally, as already stated, gradual transitions from the one into the other occur.

Horizontal Cleavage Planes

Most banded coals split quite readily along certain horizontal cleavage planes, and with some care many may be split into numerous thin sheets. On the surfaces of such specimen, and for that matter on any horizontal cleavage surface, there are almost always to be seen certain patches bearing plant structures in greatly varying numbers. Their sizes and forms may also vary considerably, from those only barely visible to the eye to those covering the whole block or more. Each patch is like an island in a more or less structureless background. (Fig. 2, plate V.) A number of different classes of structures are to be found; such as of wood, periderm, small stems or twigs, petioles, rachis, bracts, leaves, and needles; however, the structures found most often are those of wood or xylem and periderm. Patches with structures of wood are most conspicuous and stand out most sharply against the dull background and are often mistaken for patches of fusain. Although irregular forms are common, most of them approximate oblong parallelograms with the wood fibers parallel to the longer edges. Patches bearing leaf structure are often only those of fragments of leaves, although complete pinnules of the fern type are to be found. Remains of petioles and rachises are quite numerous on some surfaces. Larger stems and twigs are better observed in open pits or strip mines. These may range in length from a fraction of an inch to several feet. The surface characteristics are often well-preserved in them.

Patches Represent Solid Constituents

The patches so commonly seen on the horizontal cleavage surfaces represent solid masses of coal and not merely impressions of structures. There is, however, for each patch a counterpart in the opposite cleavage surface, which may only be an impression. On cutting into the patch with a sharp tool, a glistening layer of coal is found immediately beneath the surface of the patch; or a piece of coal may be treated mildly with Schulze's reagent, when, after the proper length of reaction, these patches may be separated as thin sheets of coal with structures on both sides, and when broken show glistening coal inside. Other methods may be used appropriately, which show that they are invariably solid masses and that the black glistening bands seen in the polished vertical surfaces consist of the same material represented by the patches seen in the horizontal cleavage planes. This shows, therefore, that many of the tiny black stripes are also the remains of woody tissues.

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PLATE V

Fig. 1. Block of Illinois No. 6 coal, Franklin County, Illinois, with polished surface to bring out the layering more clearly, showing jet black bands (anthraxylon or vitrain), grayish striated attrital bands, inclusions of fusain shown as uniform light-gray linear patches, and vertical cleavage fissures often containing mineral matter. 1/2 natural size.

Fig. 2. Horizontal cleavage surface of coal showing a number of patches largely with woody cell structures. 1/2 natural size.

Fig. 3. Thin cross section of one of the black bands or anthraxylon, being the tangential section of coalified coniferous wood showing medullary rays on the tangential surface and cross sections of bordered pits in the radial walls. X100.

Fig. 4. A part of the same section at a higher magnification to show the structure in detail; notice particularly the cross sections of the bordered pits in the radial walls. X500.

Fig. 5. A part of the same section at a higher magnification to show the structure in detail, particularly the cross sections of the medullary rays. X500.

Fig. 6. Thin vertical section of coal, being a transverse section of coalified coniferous wood and adjoining attrital matter. The wood fibers have been compressed very much, yet their structure is clearly visible. X100.

Fig. 7. Thin horizontal section of coal, including a radial section of coalified coniferous wood with bordered pits. X100.

Fig. 8. Thin vertical section of coal, including part of a black or anthraxylon band consisting of part of a coalified coniferous stem with wood and bark intact. The cell walls of the tissues of the bark have been reduced very much, so that they now consist largely of resinous cell contents. The different tissues are still distinguishable. Wood below, phloem next, and cortex above. The uppermost part of the illustration represents a resinous attritus with remains of cuticle. X100.

Fig. 9. Transverse section of a young branch of Lepidodendron selaginoides before secondary wood was formed. w - primary wood cylinder; pc - zone of phloem; c - inner cortex differentiated into three layers; c^2 - outer cortex; pd - periderm; zone of leaf-bases on the outside of periderm; lt - leaf traces; lg - ligules. (From Scott, Studies in Fossil Botany.)

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Plate V

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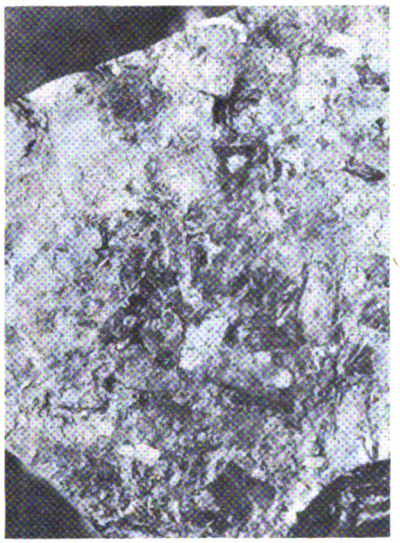

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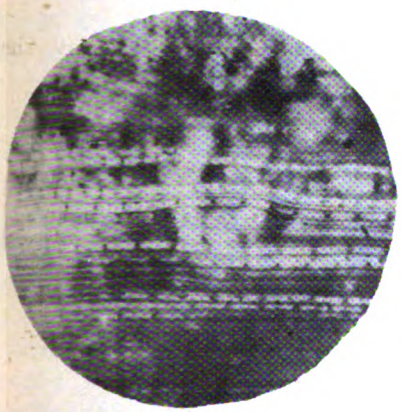

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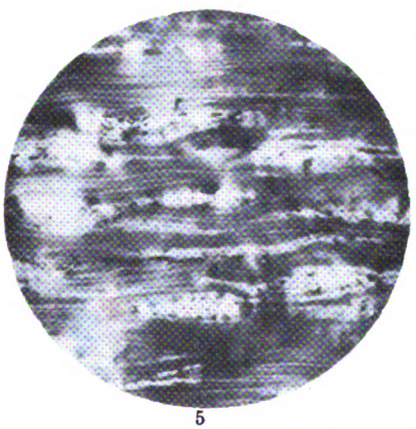

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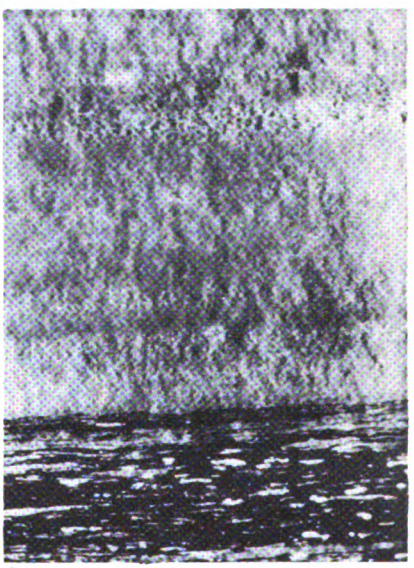

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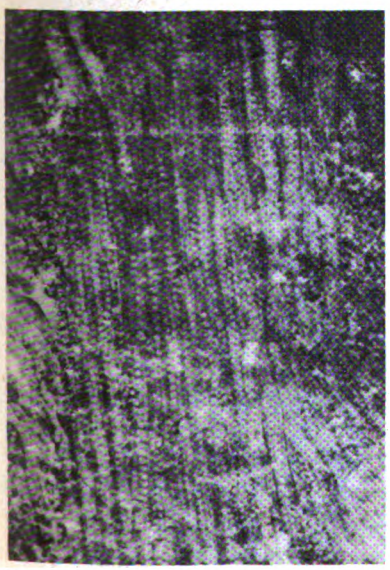

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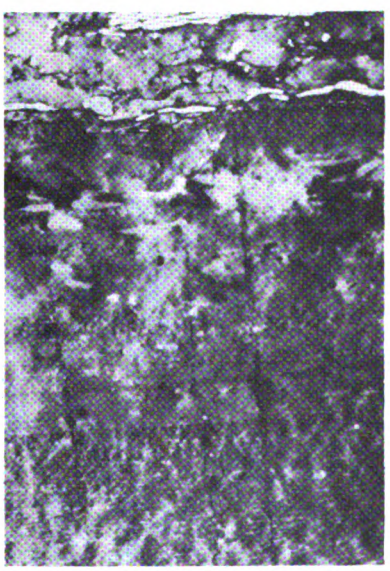

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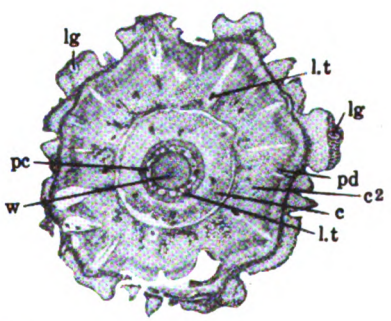

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INTERPRETATION OF THE THICKER BLACK BANDS

Let us now analyze more closely the banding as far as revealed in the lump and on the polished surface by means of the unaided eye or a hand lens. How are these objects to be interpreted? What is their real nature, and what is their origin?

The Thicker Bands

Let us first turn to the larger or thicker black bands, the strands or bands generally called vitrain, chiefly by the Europeans, and anthraxylon by us.

The most expedient method of studying coal is by microscopical examination through thin sections. For this purpose, thin sections of the specimen of coal to be examined are made first by preparing a very smooth or polished surface on one side of a properly selected block of the proper size; next, this surface is cemented to an ordinary object slide by means of a mixture of Canada balsam and marine glue of the correct consistency. The small block thus cemented to the object slide is then worked down, first by rough grinding, next by grinding with finer abrasives, and next by rubbing by hand on a very fine-grained, yellow, Belgian hone until thin enough to be translucent. Finally, the section is polished by means of a very finely divided polishing powder on a selvyt cloth. The finished section is then covered with a cover glass in the usual way. A thin section of coal thus prepared is no longer black by transmitted light but is of a delicate yellow to ruby-red color. Any one of the thicker black bands or, in other words, the so-called vitrain or anthraxylon bands is generally of a beautiful ruby-red color and at a higher magnification invariably shows some cell structure of some kind of woody tissue and clearly shows its derivation from woody tissues. The nature of the structure depends upon the kind of plant that gave rise to the band and the direction in relationship to the tissue in which cut. Structures derived from three distinct types of plants are generally distinguishable - conifers, cycadophyte, and lycopod.

Invariably, the structures of one or the other of these is found in these bands. In one specific coal, however, one or the other may predominate with the other, or both, as secondary component. In some coals, or parts of a coal bed, the structure of two of them may be found in more or less equal proportions, with the third as a minor component. The structure may be well-preserved or very poorly preserved, with all degrees of preservation between these two extremes, but no band without any structure at all has yet been found.

Coniferous Wood Structure

We have already become familiar with the structure of the stem of the conifers and have seen its transformation into peat, and later have found its remains in brown coal and lignite. The identification and recognition of its structure is therefore relatively easy.

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The most common structure of the conifers found in these black anthraxylon or vitrain bands, and of which the whole band is composed, is shown in figure 3, plate V. This is a tangential section of the structure and should be compared with figure 11, plate I, and figure 9, plate III. In it are shown distinctly the ends of the rays and the cross sections of numerous bordered pits. The latter are shown more distinctly at a high magnification in figure 4, plate V. The cross sections of the rays are better shown, at a higher magnification, in figure 5, plate V. The remains of the ray cells consist almost entirely of resinous matter. Transverse sections of the wood or xylem are also frequently encountered, but they hardly ever stand out as sharply and distinctly as the tangential or the radial sections. Figure 6, plate V, represents a transverse section. Radial sections of the xylem are brought out most distinctly in sections cut horizontally to the bedding planes of the coal. (Fig. 7, plate V.) The multiserial bordered pits are shown distinctly. In many examples, the bark is still intact with the xylem. Figure 8, plate V, shows one of numerous such examples. Often, the different tissues of the bark, such as phloem, periderm, cork, and cortex, are plainly distinguishable.

Remains of Lycopods

Other black bands contain the structures of ancient lycopods. In these we come to an order of plants quite different in structure and growth from the conifers. In the case of the lycopods, we have no recent living member of the order from which we may learn the structure of the coal-forming relatives, such as was the case with the conifers.

Although we have living forms of the lycopods for study today, there is little in them that can be used to get an adequate knowledge of the ancient forms. They are all highly specialized and greatly reduced forms. Lycopodium, which we have already examined (figs. 7 to 10, plate II), has simple external characteristics, but its anatomy is quite complex and modified along peculiar lines of its own and not like the ancient lycopods nor like any other plant. It is not easy, then, to form an idea to help in obtaining knowledge of the structure of the coal-forming members.

The paleobotanists, however, have been able to find much material in the form of impressions in the rocks and in coal balls to enable them to reconstruct a number of the members of the ancient lycopods, and have given us a clear picture of the habits, form, and sizes. There are, in the main, two great groups - Lepidodendron and Sigillaria - presenting quite different outward appearances, although their inner structures are similar. Of these, the Lepidodendrons have been studied most and are the better known. (Fig. 1, plate VIII.)

The Lepidodendrons first appeared in Devonian times, attained their maximum in the Carboniferous period, and died out in the Permian. They grew to large trees, of which trunks over 100 feet long have been found. The main stem grew up straight to a height of many feet before the crown of branches was reached. The branches as well as the roots grew dichotomously, that is, by two's. (Fig. 3, plate VIII.)

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The young stems and branches were densely covered with numerous simple leaves of needlelike form, in general short but in some reaching a length of 6 to 7 inches. When the leaves were shed, their bases remained on the stem or branch, forming the leaf cushions, which persisted on the large trunks. These leaf cushions, packed more or less close together, are of a rhombic form and give the surface of the trunk the well-known scaly appearance. (Fig. 3, plate VIII.)

Fortunately, the structure of the coal-forming plants is often preserved in the minutest detail in coal balls, and from this the general organization and structure and a complete reconstruction of the plant can be obtained as well as though from a living plant. From such material, the general structure of the lycopods has been learned. Figure 9, plate V, represents the transverse section of a very young stem of Lepidodendron selaginoides, one of the many fossil plants whose detailed structure has been obtained from coal balls, and from this the general organization of all fossil Lepidodendrons may be visualized. The central part of the stem of this species consists of the primary wood (w). It is composed of tracheids mixed with parenchymatous cells and takes the place of the pith of the conifers and other lycopods. The primary wood is surrounded by a very thin zone of secondary wood, not indicated in the illustration. On this follows the phloem, also not indicated, and the pericycle (pc). The pericycle is surrounded by the inner cortex (c). The inner cortex is sharply separated from the outer cortex (c^2) surrounding it. The outer cortex merges gradually into the periderm (pd). The inner cortex consists of parenchymatous cells. The outer cortex begins with parenchymatous cells, which gradually lengthen into fibers and merge into thick-walled schlerenchymatous fibers in the periderm. The periderm is abruptly bounded by an irregular zone of leaf bases. This represents the general structure of all lycopods and aids in the interpretation of the remaining structures of the lycopods in coal.

The periderm, being a very thick-walled, highly lignified tissue, has resisted the peat- and coal-forming processes more than the other tissues, and hence has remained in larger proportions. A number of bands consist of whole, coalified, flattened stems, in which all the tissues are represented. In these, the periderm is always the best-preserved and forms the larger part, whereas the inner cortex, phloem, xylem, and pith are represented by thin zones poorly preserved. The most prominent remains of the stem, therefore, consist either of the remains of periderm, with certain amounts of inner tissues of the outer cortex attached, or of larger or smaller fragments of periderm alone. (Figs. 1 and 2, plate VI.) The remains of periderm as found in coal, as seen in transverse sections, has very often, on the outer margin, a thin zone of poorly preserved tissue. (Fig. 1, plate VI.) This zone, although always relatively thin, may be very irregular and may vary in thickness and, when of some thickness, are often laminated or frayed into a varying number of thin strands. Beneath this zone follows a relatively thick zone consisting of thick-walled fibers of a peculiar structure. (Fig. 1, plate VI.) Beneath this zone follows a third, composed of fibers of a more ordinary nature, as shown in figure 2, plate VI. This zone gradually changes into a fourth, in which the structure is usually very poorly preserved. As interpreted from the structure as seen in the transverse section of the stem, (fig. 9, plate V), the outer zone represents the zone just under the leaf bases, the next the periderm, gradually changing into the outer cortex and the inner cortex.

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PLATE VI

Fig. 1. Thin cross section of Alma coal, Mingo County, West Virginia, with black band or anthraxylon band being the coalified periderm of a lycopod adjoining general attrital matter. X100.

Fig. 2. Thin cross section of black or anthrazylon band from the Alma coal bed, Mingo County, West Virginia, being the transverse section of the coalified outer cortex of lycopod. X100.

Fig. 3. Transverse section of the stem of a Cycadophyte. The central part represents a pith mixed with irregular black inclusions; surrounding this is a ring or zone of wood with numerous medullary rays. The wood is surrounded by a zone once occupied by the phloem, now much disintegrated and replaced by black material; on this follows the inner cortex; surrounding the inner cortex and enclosing the whole is the periderm. The periderm consists of alternating radial bands of schlerenchymatous and parenchymatous tissues. X2.

Fig. 4. Thin cross section of Pittsburgh coal, Washington County, Pennsylvania, consisting of part of the coalified stem of a Cycadophyte. X100.

Fig. 5. Thin cross section of Alma coal, Mingo County, West Virginia. This illustration represents the sections of a number of leaf bases and lower parts of leaves. X100.

Fig. 6. Thin cross section of Alma coal, Mingo County, West Virginia, consisting mostly of the sections of the remains of leaf tissues and parts of leaf bases. X100.

Fig. 7. Thin cross section of Alma coal, Mingo County, West Virginia, including a megasporangium with megaspore. X100.

Fig. 8. Thin cross section of Alma coal, Mingo County, West Virginia, including a microsporangium with microspores. X100.

Fig. 9. Thin cross section of Alma coal, Mingo County, West Virginia, including, in the central part, remains of a seed, Mitrospermum. X100.

Fig. 10. Thin cross section of Alma coal, Mingo County, West Virginia, including in the central part fragment of an annulus on the outer covering of a sporangium, frequent constituents in many coals. X100.

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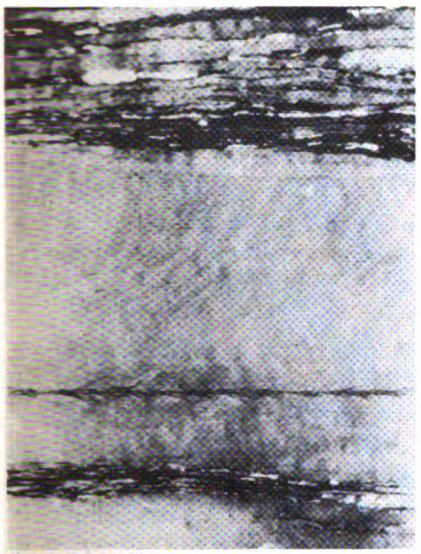
Plate VI



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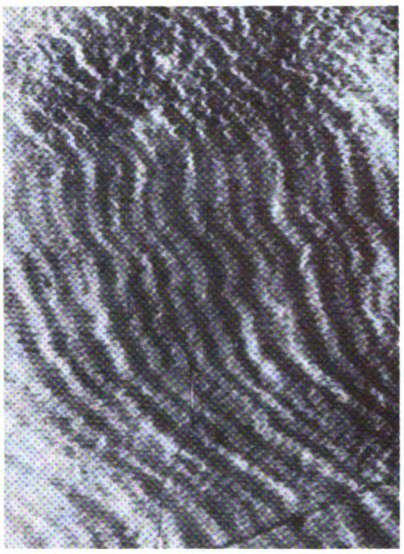

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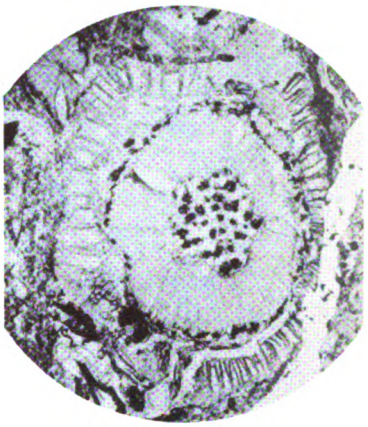

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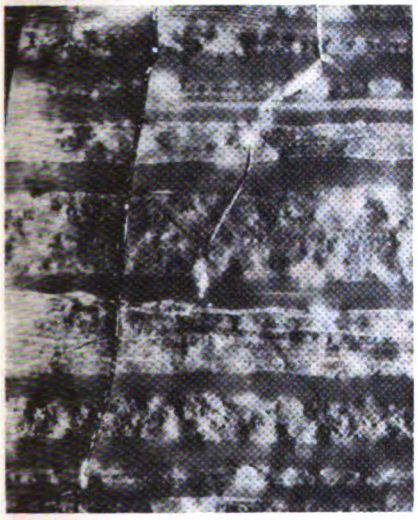

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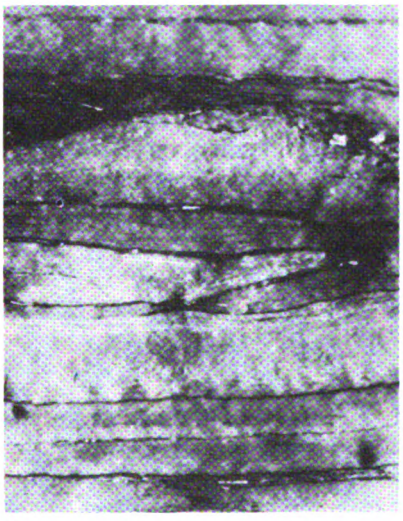

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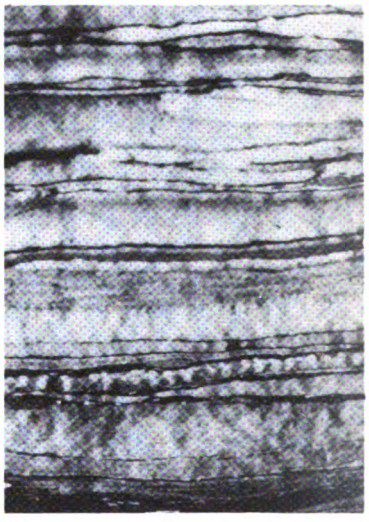

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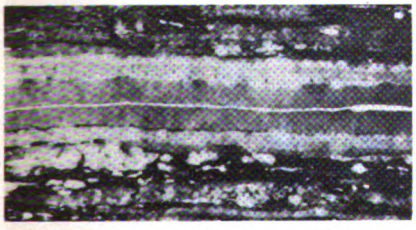

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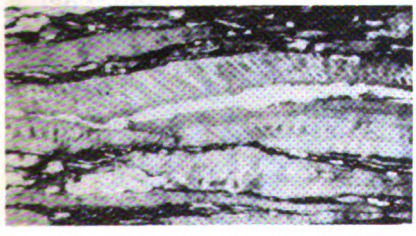

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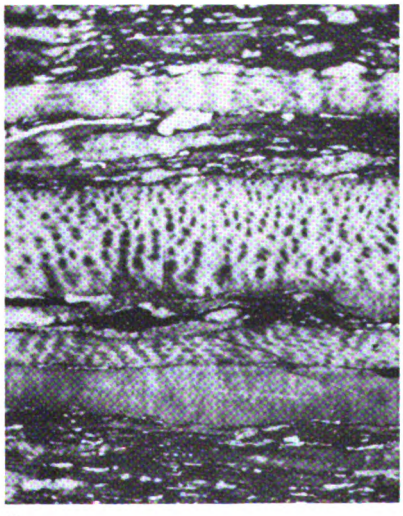

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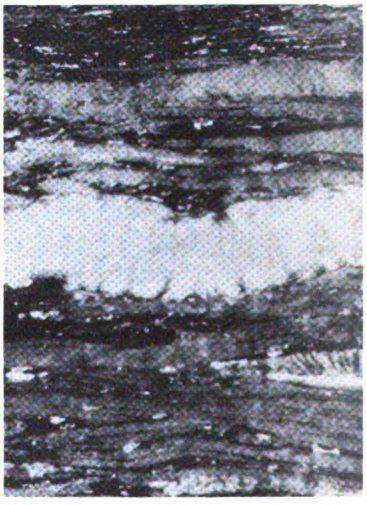

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Remains with structures of the first and second zones are found most often. Bands including remains of the first, second and third zones are also found frequently, but bands with all zones are rarely found. In cases in which the remains consist of collapsed stems these four zones are distinctly recognizable on both sides. The innermost parts, consisting of the remains of inner cortex, pericycle, phloem, xylem, and pith, are poorly preserved and confused.

Remains of Cycadophytes

Other bands again consist of the remains of cycadophytes. Cycadophyte remains are as prominent as those of the conifers and the lycopods. A great deal of their structure may be obtained through structure of the living cycads; but since the detailed structure of the ancient cycadophytes differs considerably from that of the living forms a study of the petrified remains, particularly those found in coal balls, must be resorted to.

The cycadophytes, like the lycopods, were represented by a number of genera, of which the Lyginodendron, Medullosa, and Megaloxylon are the best known. Of these, again, the Lyginodendron is the best known and may be taken as an example. In outward appearance they resembled our living tree ferns more than any other plant known (fig. 4, plate VIII) and probably were of similar sizes and habits. They differed, however, from the ferns in that all of them were seed- and pollen-bearing like the conifers and the common leafy plants. The stems of Lyginodendrons were relatively thin and slender, being from 1/8 to 1-1/2 inches in diameter. A transverse section of the stem is shown in figure 3, plate VI. The middle of the stem is occupied by a large pith, mostly parenchymous but containing irregular groups of black matter. The wood surrounding the pith consists of numerous radial series of wood fibers separated by rays radiating from the pith. Surrounding the ring of wood is the phloem, not well-preserved in the illustration and marked by an irregular ring of black matter. Outside of the phloem comes the inner cortex, consisting of a soft tissue. Next to the inner cortex follows the outer cortex. This consists of a broad zone composed of alternating radial bands of parenchymatous and schlerenchymatous tissues. It will be seen at a glance that the inner structure of these cycadophytes differs much from that of either the conifers or the lycopods.

The structure, as revealed by the petrified specimens, is clearly recognized in the structures remaining in coal, as is shown in figure 4, plate VI. As the structure of the different tissues differs considerably, the structures of the remains of these plants are much more diversified than those of the conifers. The remains of pith, xylem, phloem, inner cortex, and outer cortex all show characteristically different structures. Through fortunate finds of whole coalified stems these structures have been oriented and can now be identified independently of one another.

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PLATE VII

Fig. 1. Thin cross section of Alma coal, Mingo County, West Virginia, in which coniferous (Cordaites) leaf remains form the larger part. The dark bands in the central and lower parts represent fusain. The thinner black bands or streaks represent chiefly granular opaque matter. X100.

Fig. 2. Thin cross section of Upper Freeport coal, Allegheny County, Pennsylvania, representing a general attritus in which spores, fragments of cuticles, resinous matter, and woody degradation matters are prominent. X100.

Fig. 3. Thin section of the Pittsburgh coal, Marion County, West Virginia, representing a typical granular attritus. It contains, besides the general attrital matter, small particles of mineral matter, characteristic of this bed. X100.

Fig. 4. Thin cross section of the Green River coal, Muhlenberg County, Kentucky, representing a "fibrous" attritus, with very thin anthraxylon strands. The thin white linear constituents represent spores. X100.

Fig. 5. Thin cross section of a typical splint from the Upper Cedar Grove coal, Mingo County, West Virginia. The white linear constituents represent spores. X100.

Fig. 6. Thin cross section of the Upper Cedar Grove coal, Mingo County, West Virginia, from a very thin section of a typical splint layer, showing that the opaque matter appearing as a homogenous matter in figure 5 is really a heterogeneous mass consisting of both semitranslucent or brown matter and granular opaque matter. The irregular light areas represent spores or fragments of spores. X500.

Fig. 7. Thin section of Alma coal, Mingo County, West Virginia, from a splint layer with a high concentration of granular opaque matter among remains of highly disintegrated wood fibers -- to illustrate the nature of the granular opaque matter. X500.

Fig. 8. Thin section of Lower Cedar Grove coal, Mingo County, West Virginia, illustrating a high concentration of granular opaque matter. The grayish constituents are the remains of highly disorganized wood fibers. The small white constituents represent small spores. X100.

Fig. 9. Thin cross section of a semisplint layer from the Millers Creek coal bed, Johnson County, Kentucky. A splint coal is characterized by numerous thin bands of anthraxylon and opaque matter. The opaque matter generally consists of semitranslucent or brown matter and granular opaque matter. The white linear spots represent small spores. X100.

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Plate VII

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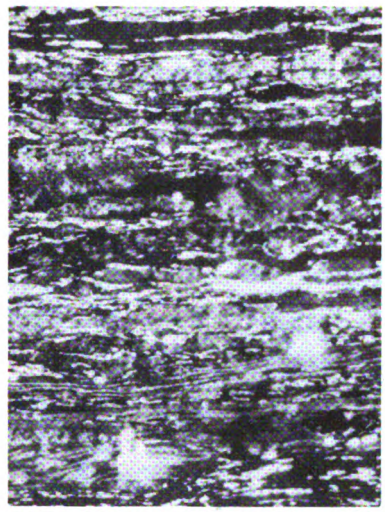

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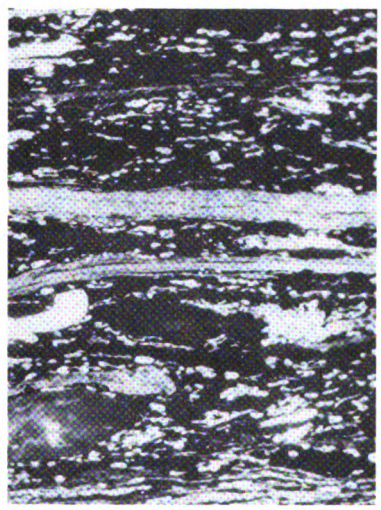

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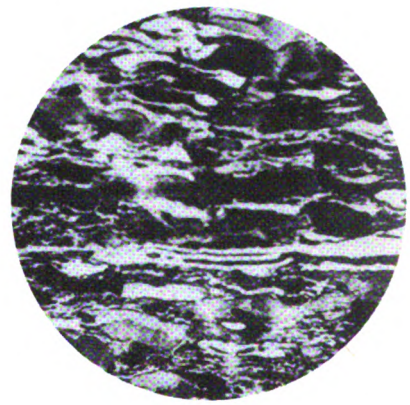

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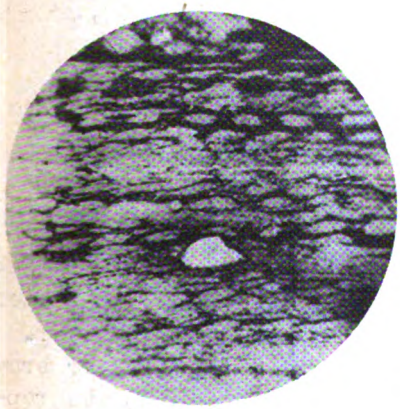

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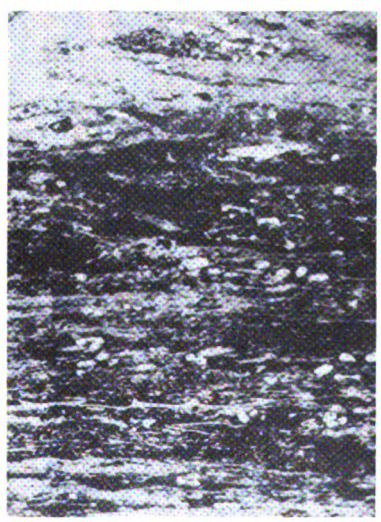

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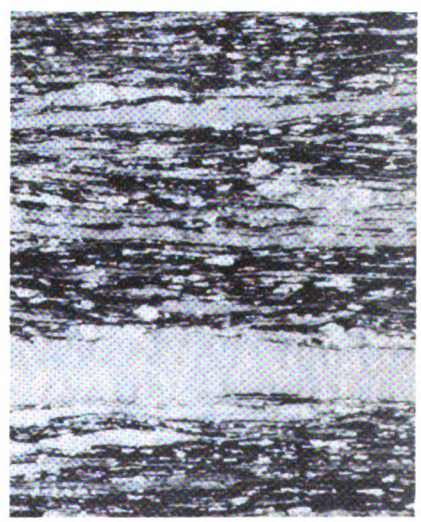

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THE THINNER BANDS

Thus far, recognition has been given to the thicker bands only. A closer examination must now be made of the thinner ones. Under the microscope it is again found that the thinner to the thinnest bands or strands in thin sections also invariably reveal some plant structure. The structure and kinds of plant matter found in them, however, is much more diversified than in the thicker bands. Although the thicker bands are almost exclusively derived from the wood and periderm or bark of stems, the smaller ones may be derived from leaf bases, leaves, petioles, rachises, sporophylls, and sporangia, as well as from the woody parts and the bark of stems. Those structures in the thinner bands derived from the woody parts of the stem are of the same origin and similar in structure as those in the larger ones, except that they have often suffered a larger degree of maceration and diminution. There is no dividing line as to size and structure of the woody derivatives from the largest and thickest to the most minute sheets and which must be counted with the finely divided attrital matter.

The most prominent structures found in the thinner strands are those of leaves and leaf bases of certain lycopods. Good examples of leaf bases are shown in figure 5, plate VI, and a good example of leaves is shown in figure 6, plate VI. Leaf bases and leaf tissues may occur singly, in twos, in threes, or more. Sometimes a considerable number are piled one upon another, as shown in figure 6, plate VI. With the leaf bases there are occasionally associated or definitely connected certain lenticular, thick-walled, well-preserved tissues that most likely represent well-known ligules. Sporophylls and sporangia also comprise a considerable part of the structures of the thin bands. Sporangia often remain connected with the sporophylls. Sporangia may enclose megaspores, as in figure 7, plate VI, or microspores, as in figure 8, plate VI. Structures as shown in figure 9, plate VI, are quite common. They probably are fragments of seed coats of some conifer. Remains of sporophylls, sporangia, leaves, and leaf bases are frequently closely associated and, their structures being quite similar, are not easily distinguishable, if at all.

The outer sclerenchymatous sporangium walls are conspicuous representatives in the thin strands, as shown in figures 8 and 10, plate VI. Remains of the leaves of the conifers are particularly well represented. (Fig. 1, plate VII.) Remains of leaves of conifers and cycadophytes, as well as of the lycopods, form an important part of coals. Besides the leaves their petioles and rachises are often conspicuously represented by the thinner bands.

The Finely Divided or Attrital Material

We have found that all the constituents in coal are the result of disintegration and maceration. From this mass, as in peat, we have so far picked out the coarser material and subjected it to examination and have found that it consists of the remains of woody tissues of the

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coal-forming plants. The thinner bands we have found to consist of both the woody tissues and the remains of leaves, leaf bases, petioles, sporophylls and seeds, and sporangia, and that there is a gradual gradation or transition in general of sizes. This gradation of sizes is continued down to sizes of particles visible only under the highest power of the microscope. This finely divided matter we shall call the attrital matter or attritus. (Figs. 2, 3, and 4, plate VII.) Again, it should be emphasized that there is no line of demarkation of sizes anywhere, from the largest and thickest bands down to the smallest attrital matter. This attrital matter must now be examined more closely, and again we shall use thin sections for the examination.

We have already become familiar with the appearance of the attritus in the polished surface of the block. (Fig. 1, plate V.) When examined in thin sections under the microscope at low magnification, it appears as a granular, grayish mass lodged between the more homogeneous dark-red bands or anthraxylon. At a higher magnification at 100 diameters, or more, it is revealed to consist of a number of different constituents, as we have already anticipated. (Figs. 2 and 3, plate VII.) When we look closely, the following constituents may be recognized:

1. Translucent humic degradation matter. - This may consist of the degradation matter of the light-colored cellulosic or lignocellulosic tissues of wood, phloem, cortex, of leaves, petioles, and rachises. It is of the same general origin as that of the thicker bands.

2. Brown or semitranslucent matter. - Certain plant cells, particularly those in the bark and leaves, are of a dark-brown color and are filled with dark-brown resinous contents. During peatification and coalification, such tissues or cells result in dark-brown constituents of a semitranslucency in peat and coal. In coal they are recognized as brown or semitranslucent humic matter.

3. Fusain. - Tissues, groups of tissues, or groups of cells of any kind may be coalified, through processes not understood, to such an extent as to resemble charcoal. These are recognized and designated as fusain, also called mother of coal and mineral charcoal. All intermediary stages between normal coal and typical fusain are found. Fusain may be formed from any plant tissue, part, or organ.

4. Granular opaque matter. - All coals contain a varying amount of matter in the form of almost submicroscopic sizes and of a dark, opaque color. Evidences go to show that this material is the result of an advanced state of decomposition, particularly of wood fibers. Certain parts of the fibers have been decomposed and macerated so highly that the micelles of which plants are composed have become visible and appear as minute dark particles either still aggregated or dispersed.

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5. Resins and resinous substances. - As has been shown, resins and terpenes abound everywhere in the conifers, in the pith, in the wood, and very abundantly in the bark and leaves. It has also been shown that these substances are not decomposed by micro-organisms. Many of the woody and cellulosic tissues associated with the resinous contents were decomposed, more or less, by micro-organisms, whereas the resins not attacked and decomposed were concentrated in various degrees. Often the tissues are completely decomposed, and the resins are scattered as individual particles as seeds separated from their pods. An appreciable part of the attritus always consists of these resinous constituents, either as free particles or enclosed in bits of tissues. The bark and leaves contain many substances besides the resins too numerous to recount. The most common and the best-known are the tannins, amorphous substances. When the tissues die, as in the transformation of the inner bark to the outer or when the leaves are shed in the Fall, tannins are changed and oxidized to brown insoluble substances known as phlobophenes. Most cell fillings of the bark and leaves are mixtures of resins, terpenes, and phlobophenes, and many other substances in smaller amounts.

6. Spore exines and pollen exines. - Spores, as already stated (figs. 7 to 10, plate II) are the asexual reproductive organs of the lower plants, such as liverworts, mosses, and ferns, including the lycopods and the calamites. The microscopic spherical bodies consist of the inner living or protoplasmic parts surrounded by a thin membrane, the intine, which is enclosed in an outer relatively thick shell or membrane, the exine. This is composed of a number of resistant substances, such as sporonine, esters of higher fatty acids, oils, and resins. All of these are very resistant to chemical reagents, oxidation, and micro-organisms. Because of this resistance, although the inner parts are decomposed, the exines remain unattacked and are concentrated in relatively large numbers and usually form an appreciable part of the attritus of all coals. Spore exines are the most conspicuous constituents in coal, readily seen on account of their clear yellow color and transparency. They are, of course, merely the shells or outer walls or coverings of spores of the coal-forming plants, such as calamites, lepidodendrons, sigillarians, sphenophylls, and cycadophytes. They may be recognized in the photographs as small linear patches. At high magnification their true nature is shown more clearly, and in cross section they appear, when whole, as collapsed rings often bearing wings or appendages. In reality, they represent collapsed spheres. Their contents have completely or almost completely disappeared. When seen in horizontal sections, where they are shown on the broad side, they appear as circular to oval and sometimes slightly triangular disks. At high magnification they reveal many forms of sculpterings, tetrasporic markings, and hairlike appendages.

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There are many different kinds and sizes of spores in coals, and two kinds are recognized with respect to size - megaspores and microspores. From a biological standpoint these also differ in function.5/

The thickness of the spore-wall varies greatly with the kind of spore from which it was derived and ranges from the tiniest film to huge, massive megaspores easily visible to the naked eye.

Pollen exines resemble spore exines in general appearance and chemistry, but they are always relatively small and very thin. It has been shown that the spores in coal, cannel coals, and oil shales are the main oil-yielding constituents. A coal, cannel coal, or an oil shale rich in spores is invariably also rich in oils.

7. Cuticles. - All leaves, fruits, and green stems of the higher plants are covered with cuticles to protect them from insects, bacteria, fungi, weather, and other injuries. (Figs. 5 and 6, plate II.) These are often covered with a layer of wax in the form of a film or hairlike processes or as granules. In thin sections, they appear as bright golden-yellow bands, often found in pairs and commonly having serrated borders. The substances forming the cuticles are similar in chemical composition to those of spore exines, and, like them, are very resistant to decay and chemical reactions and for that reason are common objects in coal.

TYPES OF COALS

Considering the coals as a whole, the constituents represented in the foregoing sections are to be found in varying proportions of concentrations in all ordinary coals, and the relative amounts of each of these constituents determine the nature of a coal and form the basis for classification by types.

In most of the common and best-known coals, all the constituents named are to be found; that is, thicker bands consisting of the remains of either xylem or wood, woody tissues, or periderm; thinner bands composed of the remains of leaf bases, leaves, sporophylls, sporangia, petioles, or rachises, as well as those of wood and periderm, and the still more finely divided attrital matter or attritus, together giving the coal a banded or striped appearance, and for that reason are commonly called "banded coals."

5/ Editorial comment: The various kinds and sizes of spores in coals are usually divided into two groups - megaspores, or female spores, and microspores, or male spores. Oftentimes the female spores are larger than the male spores.

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In other coals, the larger and the finer bands are wanting, and the more finely divided attrital matter alone forms the coal and lacks a definite bandedness. Such coals are generally classed as "nonbanded coals." Cannel coals and boghead coals are classed as "nonbanded coals."

Methods of Type Classification

In order to determine the microscopic composition on which the classification into types is based, complete columnar sections of the coal bed are procured, usually in lumps of convenient size. From these lumps, smaller blocks, measuring 3 to 4 inches in diameter and of convenient heights, are cut by means of a bakelite-carborundum saw, so that the blocks, when put end to end in the proper way, represent the total thickness of the coal bed. One side of the block, preferably the butt face, is polished in order to bring out the layering more sharply for comparison. (Fig. 1, plate V.) From one side of each of these blocks, a second column, measuring approximately 3/4 inch on each side, including the polished surface, is cut. From this column, also representing the complete thickness of the bed, thin sections are prepared and numbered consecutively from the floor up. These thin sections represent all the coal except that lost by the thin saw used to cut the column into proper sections. In each of the thin sections, the relative amounts of anthraxylon, translucent attritus, opaque attritus, and fusain are determined and tabulated. From these determinations, the whole bed is classified with respect to bandedness, types, and subtypes.

Banded Coals

In the banded coals, both the bands and the attritus are equally important. It has been the endeavor to show that the thicker bands represent the larger fragments of the more woody tissues of plants, that the finer bands and attritus represent the degradation matter of any and all plant parts, and that remains of leaves, leaf bases, sporophores, sporangia, and more finely divided, light-colored, translucent humic matter, brown humic matter, granular opaque matter, fusain, resins, spores, pollens, and mineral matter are recognized in it. Furthermore, it has been found that a high concentration of one or the other or lack of the concentration of any one has determined the nature of the coal.

In nature, there are three classes of banded coals that have always been differentiated in this country through their outward appearance, general nature, and characteristics. These are "bright coals," "semi-splint coals" (often called block coals), and "splint coals." It also has been recognized for a long time that these coals differed in their uses and usually in their chemical analyses.

Through microscopic examination it was found that they vary widely in their composition, the fundamental differences being in the composition of the attritus and the nature of the anthraxylon. "Bright coal" is composed of anthraxylon and an attritus in which translucent humic matter is the characterizing component, and for lack of a better name the term "bright coal" has been retained.

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A semisplint is composed of anthraxylon and attritus, usually in more or less equal proportions, brown and granular opaque matter being the characterizing components of the attritus.

A splint coal is composed of anthraxylon and attritus, in which the anthraxylon usually forms the smaller part, brown matter and granular opaque matter being the characterizing components of the attritus.

Banded coals, differentiated by these characterizing components, have been classified as types of coals to distinguish them from coals whose differences are characterized by degrees of coalification or metamorphism in the classification of coal by rank and determined by chemical analyses and calorific values.

Bright Coal

A coal composed of anthraxylon and an attritus, in which the translucent cell-wall degradation matter or transulucent humic matter predominates, is termed a "bright coal." This type embraces the larger number of coals and is, therefore, often referred to as common or ordinary coal. All the Paleozoic coals thus far discussed were of the bright coal type and shown in figure 8, plate IV, figures 1 to 8, plate V, figures 1 to 10, plate VI, and figures 1 to 4, plate VII.

The two components, anthraxylon and attritus, may be found in all proportions, regardless of the nature of one or the composition of the other; the relative proportions of one or the other determines the nature of a coal.

When a coal or a layer of coal is composed largely of anthraxylon, solid or fibrous or both solid and fibrous, at a ratio of anthraxylon to attritus (arbitrarily chosen) of more than 3 to 1, it is classed as an anthraxylous coal. If, on the other hand, a coal is composed largely of attrital matter at a ratio of less than one part of anthraxylon to three parts of attritus, it is classed as an attrital coal. Coals of these two limiting ratios are easily distinguishable by their differing characteristics. An anthraxylous coal is glossy and fragile, whereas an attrital coal is dull, grayish, compact, and tough.

Most coals, however, lie between these two extremes in composition. In coals of intermediary composition, the ratio of anthraxylon to attritus ranges from 3:1 to 1:3. This range is arbitrarily divided further into two groups with a ratio of anthraxylon to attritus of 3:1 to 1:1 and 1:1 to 1:3; hence, the following subtypes of coals may be recognized with respect to the relative proportions of these two components:

	Subtype name	Ratio of anthraxylon to attritus
1.	Anthraxylous	Greater than 3:1
2.	Anthraxylous-attrital	3:1 to 1:1
3.	Attrital-anthraxylous	1:1 to 1:3
4.	Attrital	Less than 1:3

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Bright coals may be classified further with respect to the thickness of the anthraxylous units. This classification is unimportant with respect to the constitution of coal but is of considerable importance with respect to macroscopic appearance and friability.

When the anthraxylon in a coal consists of bands over 2 mm. thick, arbitrarily chosen, it is said to be coarsely banded; when of medium thickness (between 0.2 and 2 mm.), it is said to be finely banded; and when less than 0.2 mm. thick it is said to be microbanded. Often the anthraxylon elements are so very thin as to appear as threads or fibers in cross sections. These are termed fibrous anthraxylon; when still smaller, they are classed as fibrous attritus. The different subclasses of banding may overlap or intermix, making possible a microbanded to finely banded coal, a microbanded to coarsely banded coal, or a finely to coarsely banded coal.

Coals may be classified further with respect to the concentration of their constituents. The various constituents of the attritus may be present in varying concentration in different coals or in different layers of the same coal bed. All may be present in more or less equal proportions, one or the other may predominate, any two or three may predominate in more or less equal proportion, or any one may be entirely or largely absent; but never is one or the other found alone. The predominance of one or the other of these constituents therefore largely determines the nature of a bright coal, particularly in the attrital subtypes.

By virtue of the predominance of the constituent, the following classes of bright coals are recognized:

1. Typical bright coals. - Translucent matter predominates. The attritus, irrespective of the proportion of anthraxylon to attritus, may be composed predominantly of translucent humic matter in which spores, cuticles, resins, finely divided fusain, and brown matter may be represented in minor proportions. A large number of the bright coals are of this nature and may be designated as typical bright coals. Such coals may consist of any of the subtypes noted above - anthraxylous, anthraxylous-attrital, attrital-anthraxylous, or attrital, coarsely banded, finely baded, etc.

2. Spore-rich coals - Although spores are always present in all coals, here and there whole beds of coal or certain layers of coal are encountered in which spores are found in very large numbers and, hence, largely influence their nature. Such coals are termed "spore coals" or "spore-rich coals." Certain layers in the upper part of the Pittsburgh bed are spore-rich.

3. Resinous coals. - Similarly, whole coal beds, but more often certain layers, contain a large amount of resinous matter. Such coals or layers are encountered more often in the younger coals but are by no means lacking in the Paleozoic coals.

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PLATE VIII

Fig. 1. Part of reconstruction of a Carboniferous swamp forest in the Field Museum at Chicago. The two trees in the left foreground are Sigillarias, the plants with the fernlike leaves are Cycadophytes. The big tree near the opening is a Sigillaria, the slender, straight tree to the left is a conifer (Cordaites), the trees in the right background are Lepidodendrons. The trunk lying in the foreground is that of a Sigillaria.

Fig. 2. Reconstruction of an ancient conifer, Dorycordaites, showing roots, trunk and crown; the latter is composed of branches bearing large lanceolate leaves and flowers. The trunk is shown too short. (After Grand 'Eury and Scott, Studies in Fossil Botany.)

Fig. 3. Reconstruction of an ancient lycopod, Lepidodendron elegans, showing trunk branches, leaves, and cones. (After Grand 'Eury and Scott, Studies in Fossil Botany.)

Fig. 4. A Cycadophyte, Neuropteris decipiens, from a reconstruction in the Field Museum at Chicago, showing trunk, leaves, and seeds. The photograph was taken while the individual plants were being made. (After Chamberlain, Gymnosperms, Structure and Evolution, The University of Chicago Press, 1934.)

Fig. 5. Block of splint coal from the Dorothy coal bed, also called the Winifrede bed, Kanawha County, West Virginia. Notice the irregular fracture and the thin irregular black or anthraxylon bands. 1/2 natural size.

Fig. 6. Block of semisplint coal from the Hazard No. 4 coal bed, Perry County, Kentucky. This coal is also called block coal. 1/2 natural size.

Fig. 7. Coke residues from the Fischer low-temperature assay of layer samples. (1) from the bright coal layer, (2) from the splint layer, (3) from the mixed layer. See chart, plate XI.

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Plate VIII

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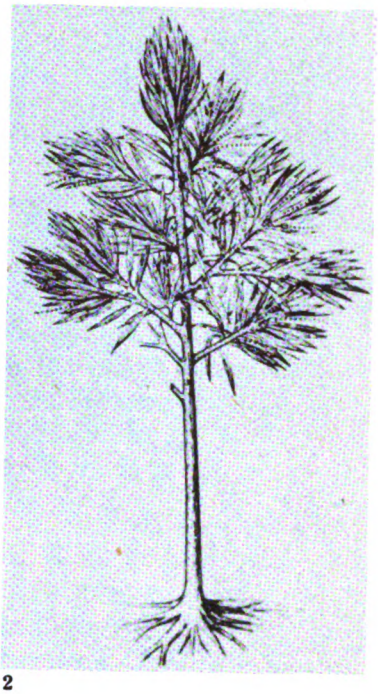

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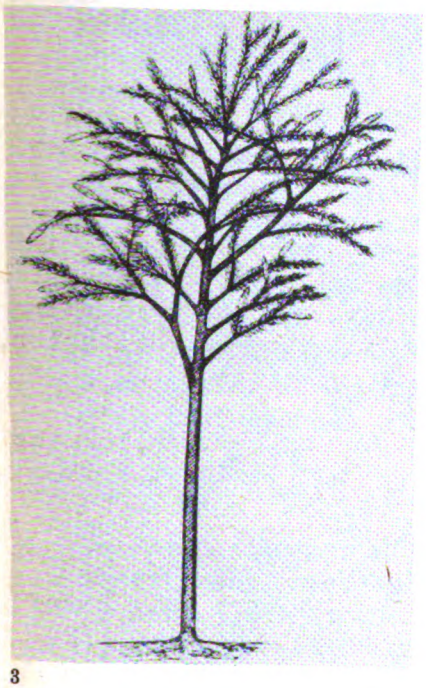

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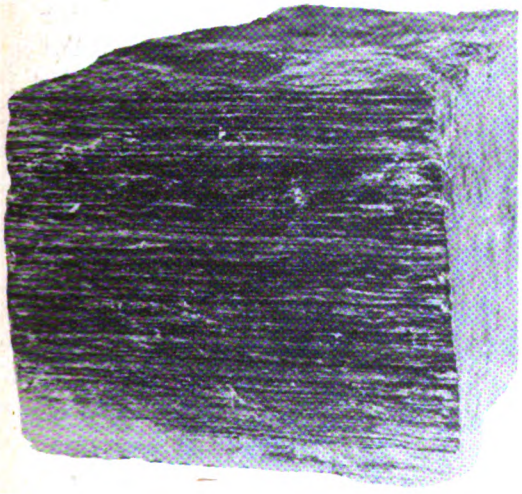

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4. Coals rich in cuticles. - Cuticles or fragments of cuticles, usually in small proportions, are found in all coals, but occasionally cuticles remain in large proportions in a whole bed or certain layers of a coal bed. One such coal is found near Moscow, U.S.S.R., and is called "paper coal."

5. Leaf coals. - Leaves have contributed largely to most coals. Approximately one-third of the matter in the Lower Sunnyside coal from Utah is derived from leaves. Certain layers of the No. 6 bed of Illinois and of the Upper Freeport bed, Pennsylvania, contain a large proportion of leaf-degradation matter. In some layers, leaf-degradation matter even predominates. It consists of a number of specific constituents, of which resins, resin-tannins, and brown matter predominate, usually with cell-wall degradation matter as a minor constituent. Occasionally thick-walled hypodermal tissues are also prominent.

6. Bark in coals. - Remaining tissues of bark are found in almost all coals. They are particularly recognizable in certain younger coals where a large proportion is derived from bark. A coal in China is composed very largely of the remaining tissues of bark. Certain layers in the Paleozoic coals also are shown to be derived largely from the same tissues. Residues of bark are often recognized through the association of characteristic brown cell walls and dark brown cell inclusions.

Splint Coal

In certain layers of coal in many beds, the opaque matter forms the predominant part, whereas the dark bright bands or anthraxylon form but a small part. The opaque constituents consist of two kinds of material - a semitranslucent or brown matter and a granular opaque matter. Such coals are called splint coals in this country, durain or hards in England, and Mattkohle or Durit in Germany.

A splint coal, therefore, is one composed of anthraxylon and attritus, of which the latter, consisting chiefly of brown cell-wall degradation matter and granular opaque matter, forms the larger part. Translucent humic matter, resins, and finely divided fusain are present in smaller proportions, and spores in greatly varying proportions. Figure 5, plate VIII, shows a chunk of typical splint coal, and figure 5, plate VII, a thin section of a typical splint.

Splint coals differ radically from either the bright or semisplint coals, owing to their dull grayish color, greater hardness, solidity, lower friability, and higher specific gravity. They break with an irregular fracture, making irregular, often sharp-cornered, blocks. Most of them are irregularly microbanded to finely banded. (Fig. 5, plate VII.) When ground on a glass plate with fine abrasive, the ground surface

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assumes a brownish-black color. All attempts to polish the surface failed; it was given a dull, grayish-black appearance, but never the high polish assumed by the bright coals.

In preparing thin sections from a typical splint coal, it is difficult to get them thin enough to be transparent. Sections thin enough for the ordinary bright coal to be satisfactorily transparent are altogether too thick for splint to be translucent and still appear to consist largely of a dark, opaque, homogeneous substance. In this dark mass, at such thicknesses, appear embedded relatively few thin, irregular, dard-red strands of anthraxylon, a few dark-red, translucent, humic particles, a greatly varying number of spores, and a varying number of resin particles. As the section is ground thinner, more and more of it becomes translucent, being first dark brown and finally grayish brown, so that the opaque ground mass is resolved into a heterogeneous mass composed of a variety of definit constituents of varying translucency, size, and complexity mixed with a dark, granular, opaque matter. The translucent matter is dark brown to grayish brown and is called brown matter in order to distinguish it from other constituents.

When examined more closely, the brown matter (fig. 6, plate VII) is found to consist of irregular, angular to round, lumpy constituents varying greatly in both size and form. It is plainly derived from certain parts of plant tissues, groups of plant cells, and fragments of plant cells. Its characteristic form, color, and general appearance give evidence that much is derived from the bark of the coal-forming plants.

The granular opaque matter invariably associated with the brown matter in varying proportions consists of innumerable very small or coarsely colloidal black or very dark particles (fig. 7, plate VII). They have a granular appearance, or when present in high enough concentrations give a granular appearance to the attritus (fig. 8, plate VII) and hence are called, in order to distinguish this matter from other constituents, "granular opaque matter."

This matter occurs as scattered particles more or less densely aggregated, as concentrations more or less closely packed into lumps, bands, or sheets. The particles often surround other constituents in thin layers or sheets or fill the interior of coalified tracheids and fibers. When in higher concentrations, they render the attritus totally opaque.

There is evidence that this granular opaque matter is the result of advanced biological decomposition and, further, is acted upon during later coalification of certain parts of the lignified tissues, particularly of the wood tracheids of conifers. It appears that the micelles of the secondary wall of the tracheids or wood fibers have been highly differentiated darkened, and disintegrated. In a number of coals complete transition stages from normal coalified coniferous xylem to a completely dispersed state of the granular opaque matter as components of typical splint are to be found. (Fig. 8, plate VII.)

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The brown matter and the granular opaque matter are found in varying proportions in the attrital matter of all splints; in most cases, however, the brown matter predominates.

Finely divided fusain is also invariably present but always forms but a small part of the attritus.

The anthraxylon generally consists of thin, irregular, dark, resinous strands from a few microns to only a few millimeters thick. The thinner strands predominate and are located irregularly, often with but little tendency to parallelism. Frequently they are frayed and resolved into mere shreds. (Fig. 5, plate VII.)

Spores are always present in greatly varying amounts, but often in large proportions, and then lend special characteristics to the coal.

Semisplint Coal

Some coals consist of more or less equal proportions of thin, bright, black or anthraxylon bands and opaque matter. The opaque matter consists, as in the splint, of semitranslucent or brown matter and granular opaque matter. Such coals are called semisplint coals.

A semisplint coal, therefore, is one in which the proportions of anthraxylon and attritus are more or less equal, but the attritus of which is essentially composed of brown and granular opaque matter in varying proportions. Translucent humic matter, spores, pollens, and finely divided fusain are always present in small proportions. In certain respects its composition is a medium between a bright coal and a splint; in other respects it has characteristics of its own.

In mining, the coal breaks up into fairly regular parallelepiped blocks, and for this characteristic it has come to be known in the trade as "block coal." The majority of samples of block coals have proved to be semisplint. It is usually finely banded to micro banded, with more or less definite parallel layering. (Fig. 6, plate VIII.)

In thin sections, the coal appears definitely striped. The anthraxylon consists of relatively thin to very thin, straight, compact, smooth bands, in contrast to the irregular, crooked, frayed bands of the splint coals. (Fig. 9, plate VII.)

Both the brown and the granular opaque matter are of similar appearance as in the splint, and in all probability are of the same origin.

Translucent cell-wall degradation matter is always present in small amount. It is of the same general nature as in all coals.

Spores, finely divided fusain, resins, and leaf-degradation matter are invariably present in small proportions.

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The Occurrence of Types

By far the largest proportion of our coals fall under the type of bright coals; splint and semisplint coals almost always occur in association with some bright coals. Only one case is known, that of the Silush bed of West Virginia, which is composed of splint and semisplint only. As far as is known in America, well-developed splints occur only from the lower part of the Middle Pottsville, beginning with the Beckley bed, up to the Middle Kittanning in the Allegheny series. No splint coal has been reported from the Lower Pottsville, and all coals in it are of the "gas" or "bright-coal" type. The Middle Pottsville coals contain relatively few splint coals. The coals of this division are called transitional coals by the West Virginia Geological Survey. The greatest amounts of splint coals are found in the Upper Pottsville, and in the lower part of the Allegheny formation up to and including the Middle Kittanning. There are no splint coals of any note, as far as now known, above the Middle Kittanning.

As stated, splint coals almost always are associated in the form of thinner layers interlayered between thicker layers of bright coals and almost always comprise the smaller part. Most coals containing splint also contain semisplint. Relatively few contain splint only in association with bright coal. The splint layers, or both splint and semisplint layers, cut a coal bed into a number of type layers. For example, the Chilton bed of West Virginia contains the three types, dividing the bed into 6 layers, from the floor up: Bright coal, semisplint, bright, semisplint, bright, and splint. The lower Cedar Grove bed of West Virginia (plate IX) is made up of three layers: Bottom layer, a bright coal; middle layer, a splint coal; and top layer, a mixture of semisplint, splint, and bright coal. The Pratt bed (plate X) is layered in the following order from the floor up: Bright, semisplint, splint, and bright, making four layers. The Elkhorn bed at Jenkins, Ky., about 50 inches thick, containing the three types, may be separated into as many as 20 definite type layers. These comprise 55 percent bright coal, 29 percent semisplint, and 16 percent splint. Many of the splint bands are thin, but none are less than 1 inch thick, the thickest being about 8 inches; the thickest bright-coal layer is approximately 20 inches thick. The Beckley bed (plate XI) in Raleigh County, West Virginia, is composed of bright, splint, and bright mixed with semisplint. The composition of the bed as a whole is: Bright, 77 percent; splint, 17 percent; and semisplint, 6 percent.

Properties of Types of Coal

It has been shown that, according to petrographic and microscopic analyses, the banded coals may be classified into bright coals, splint coals, and semisplint coals and their subtypes, and that a coal bed may consist of a number of type layers. The question naturally arises as to what are the specific properties which each of these may possess, and the behavior each may manifest in their various uses, and what are the specific differences between them, if any, in these respects.

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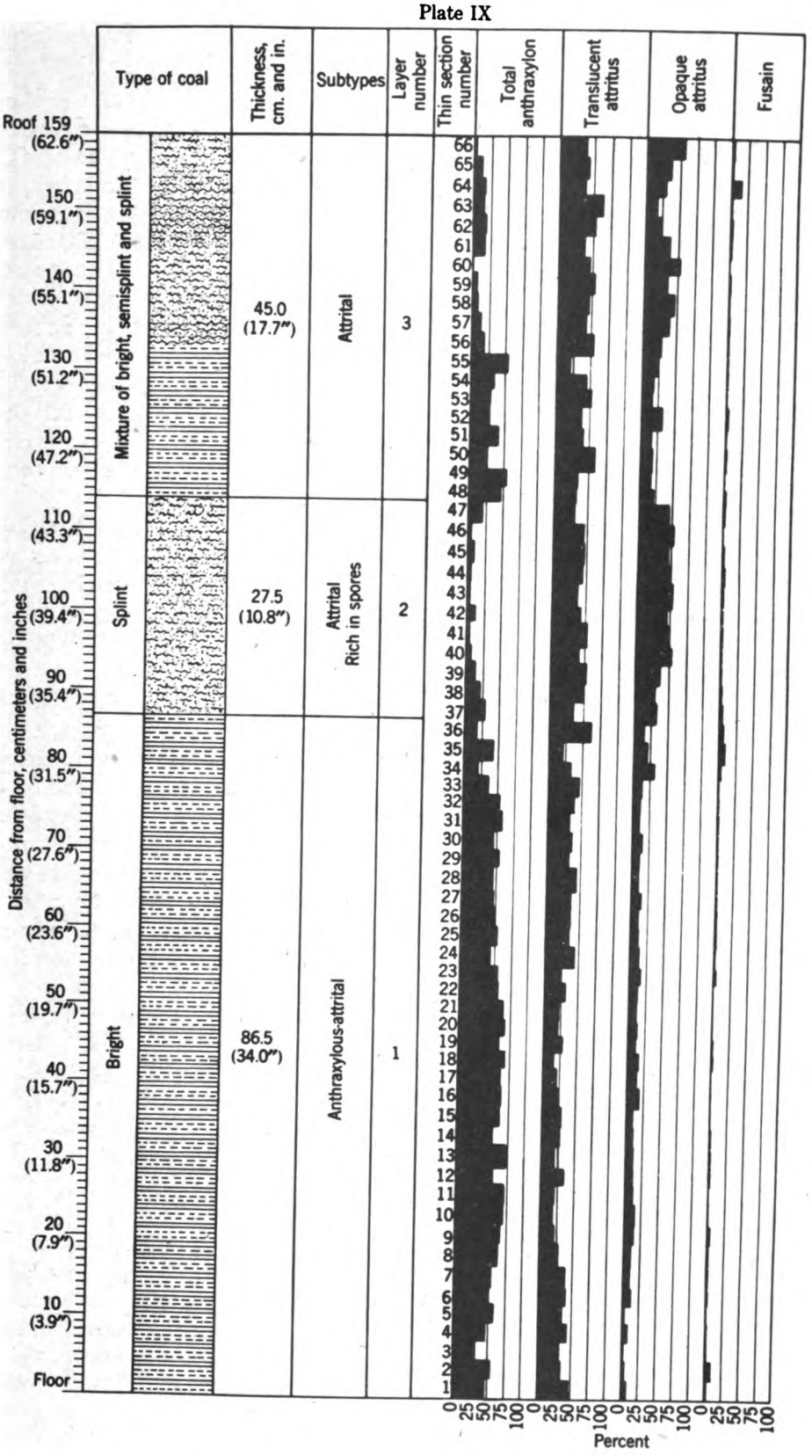
Plate IX



Graphical representation of types of coal and percentage of components in the Lower Cedar Grove bed, Mingo County, West Virginia.

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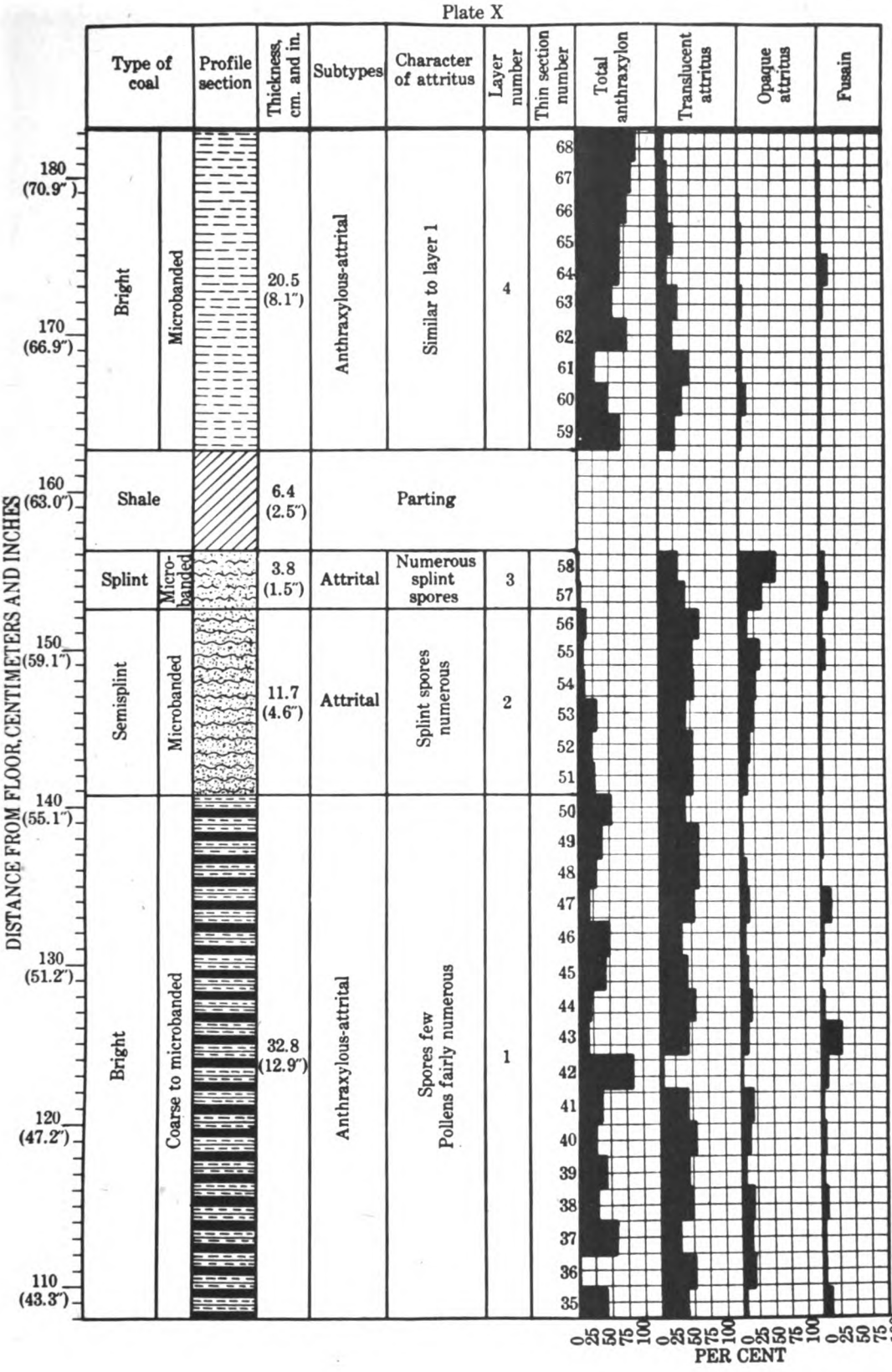
Plate X



Graphical representation of types of coal and percentage of components in the Pratt coal bed, Jefferson County, Alabama.

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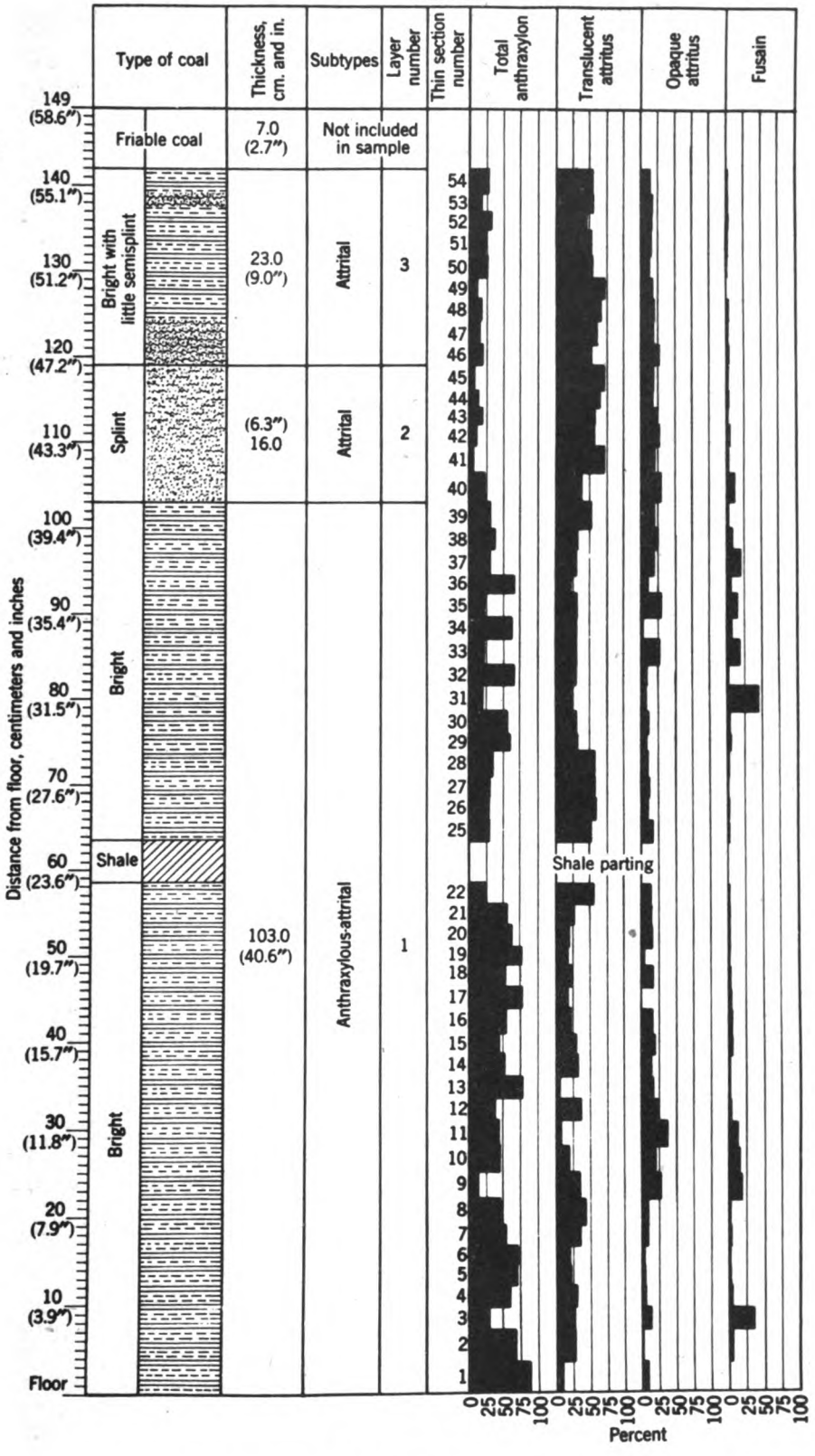
Plate XI



Graphical representation of types of coal and percentage of components in the Beckley coal bed, Raleigh County, West Virginia.

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In order to determine some of their properties, the different types and subtypes, and the specific differences between them, certain components were separated from the coal and certain layers of typical bright, splint, and semisplint coals and layers with subtype variations were selected and subjected to microscopic examination, chemical analyses both proximate and ultimate, Fischer low-temperature assays, agglutinating-value determinations, plasticity measurements, and calorific determinations. Many data have been accumulated, but a few examples only will have to suffice to show the general trend. Table 1 gives the chemical analyses of some of the coal-forming constituents.

Table 2 gives the petrographic composition, moisture, and ash content, chemical analyses, both proximate and ultimate, on the moisture and ash-free basis, and calorific and agglutinating values of the Dorothy bed, the Upper Cedar Grove, the Lower Cedar Grove beds of West Virginia, the Pratt bed of Jefferson County, Alabama, and the Beckley bed of Raleigh County, West Virginia.

In this table, the beds are arranged in decreasing order of the volatile content of the bright-coal layer in them. The differences in their chemical and physical characters in general decrease with an increase in rank. The differences noted in the Beckley coal, the highest in rank of the series, are but slight, yet in physical properties, as shown in the coke button and as shown in plate XI, of (1) bright, (2) splint, and (3) mixed layer are considerable.

From the work as a whole, a number of general conclusions may be drawn:

1. Anthraxylon in all cases contains less volatile matter than the bright coal from which it was separated. It may have a higher or a lower value than the splint of the same bed, depending on the composition of the splint.

2. All samples of anthraxylon contained relatively low amounts of ash.

3. The semi-opaque or brown matter, one of the characterizing constituents of splint coals, has a volatile content greatly below that of the bright coal of the same bed. This difference may be as great as 9.5 percent when compared with the anthraxylon of the same bed, and as high as 17.4 percent when compared to a spore-rich layer of the same bed. It has little swelling power. The coke button obtained from splint coal rich in brown matter is dense and granular, with little cell structure. A coal rich in brown or semi-opaque matter always gave a slight but noticeable increase in total carbon over that of bright coals of the same bed. The calorific value of pure brown or semi-opaque matter was only slightly less than that of the anthraxylon of the bed from which separated.

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4. The presence of spores in bright coal always tended to increase volatile matter. This increase may be as much as 7.9 percent over pure anthraxylon.

Spores in splint coal tend to offset the low-volatile content of the semi-opaque matter. A spore-rich splint coal may have a proximate analysis similar to that of a bright coal. In all instances, spore-rich coal gave a higher calorific value than the anthraxylon.

A higher hydrogen content was noticed in virtually all samples of spore-rich coal.

5. Although the chemical analyses of the various types of coal may differ but slightly, and in some cases may be almost identical, the differences in their behavior in their uses may be considerable.

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TABLE 1. - Analyses of individual coal-forming constituents

Coal	Sample	As-received basis, percent		Moisture- and ash-free basis							
				Proximate analysis, percent		Ultimate analysis, percent					Calorific value,
		Moisture	Ash	Volatile matter	Fixed carbon	H	C	N	O	S	B.t.u./lb.
Pittsburgh bed, Edenborn mine, Fayette County, Pa.	Pure anthraxylon	1.3	2.0	35.9	64.1	5.5	85.8	1.7	5.9	1.1	15,280
	Spore-rich attritus	1.0	4.8	38.0	62.0	5.7	85.8	1.9	6.0	.6	15,380
	Composite of face samples	1.8	7.0	36.2	63.8	5.3	85.2	1.6	6.6	1.3	15,260
Chilton bed, Boone No. 2 mine, Logan County, W. Va.	Pure anthraxylon	1.7	2.2	34.2	65.8	5.4	85.2	1.6	7.2	.6	15,100
	Pure, opaque attritus	1.2	9.1	24.7	75.3	4.5	87.5	1.4	6.2	.4	14,980
	Largely opaque attritus	1.2	11.4	28.4	71.6	4.7	86.8	1.4	6.7	.4	15,000
	Spore-rich attritus	1.3	2.8	42.1	57.9	5.9	85.2	1.6	6.7	.6	15,440
	Fusain	.9	8.6	19.8	80.2	4.0	89.3	.7	5.7	.3	14,980
	Mine sample	2.4	4.4	39.4	60.6	5.7	85.3	1.6	6.7	.7	15,170
No. 2 Gas bed, Point Lick No. 4 mine, Kanawha County, W. Va.	Pure anthraxylon	1.7	1.3	36.7	63.3	5.4	84.5	1.6	7.9	.6	15,020
	Spore-rich attritus	1.0	3.9	44.4	55.6	5.8	85.4	1.4	6.9	.5	15,400
	Fusain	1.1	4.1	17.9	82.1	3.6	89.8	.7	5.3	.6	14,930
	Pillar section	1.9	2.7	40.6	59.4	5.6	84.2	1.5	7.8	.9	15,140
Mary Lee bed, Flat Top mine, Jefferson	Pure anthraxylon	1.0	1.8	30.2	69.8	5.4	87.1	1.9	4.7	.9	15,430
	Composite of face samples	2.4	13.7	31.4	68.6	5.6	86.9	1.9	4.3	1.3	15,230

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TABLE 2. - Microscopic composition and chemical properties of layers from several coal beds

Coal	Layer	Percent of layer				As-received basis, percent	
		Anthraxylon	Attritus	Opaque attritus	Fusain	Moisture	Ash
Dorothy	1. Mixture, bright, splint, semisplint	18	45	35	2	1.1	4.8
	2. Bright	29	60	11	0	1.2	2.9
	3. Mixture, splint, semisplint.	14	54	30	2	1.3	3.2
	4. Splint	12	46	40	2	1.3	5.6
Upper Cedar Grove	1. Bright	59	29	11	1	2.1	5.5
	2. Mixture, splint, semisplint.	32	35	31	2	1.7	7.4
	3. Splint	12	38	49	1	1.7	5.4
	4. Mixture, bright, splint, semisplint	34	40	23	3	1.8	6.5
Lower Cedar Grove	1. Bright	54	32	12	2	1.4	3.2
	2. Splint	10	44	45	1	1.3	4.8
	3. Mixture, bright, splint, semisplint	22	45	30	3	1.2	5.0
Pratt	1. Bright	53	36	6	5	1.3	2.3
	2. Semisplint	20	55	21	4	1.1	4.4
	3. Splint	4	37	51	8	.9	10.8
	4. Bright	67	25	4	4	1.2	5.3
Beckley	1. Bright	49	31	13	7	0.8	3.6
	2. Splint	12	60	24	4	.7	2.2
	3. Mixture, bright, semisplint.	21	59	17	3	.8	1.1

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TABLE 2. - Microscopic composition and chemical properties of layers from several coal beds (Continued)

Coal	Layer	Moisture- and ash-free basis: Proximate analysis, percent: Volatile matter	Fixed carbon	Ultimate analysis, percent: H	C	N	O	S	Calorific value, B.t.u./lb.	Agglutinating value: Kilograms	Sand:coal ratio
Dorothy	1. Mixture, bright, splint, semisplint	36.3	63.7	5.4	86.9	1.6	5.4	0.7	15,430	4.8	15:1
	2. Bright	41.4	58.6	5.9	85.5	2.0	5.9	.7	15,470	6.6	15:1
	3. Mixture, splint, semisplint.	35.9	64.1	5.4	86.7	1.7	5.6	.6	15,420	4.6	15:1
	4. Splint	35.2	64.8	5.3	87.0	1.6	5.5	.6	15,390	3.3	15:1
Upper Cedar Grove	1. Bright	39.4	60.6	5.7	84.7	1.5	5.7	2.4	15,250	7.6	15:1
	2. Mixture, splint, semisplint.	38.6	61.4	5.6	85.7	1.5	5.9	1.3	15,300	7.6	15:1
	3. Splint	39.8	60.2	5.6	86.1	1.4	6.0	.9	15,330	3.8	15:1
	4. Mixture, bright, splint semisplint	39.2	60.8	5.6	84.6	1.5	5.4	2.9	15,220	7.6	15:1
Lower Cedar Grove	1. Bright	37.9	62.1	5.7	85.9	1.7	5.8	0.9	15,360	7.6	15:1
	2. Splint	35.0	65.0	5.5	87.4	1.5	5.0	.6	15,370	4.3	15:1
	3. Mixture, bright, splint, semisplint	37.6	62.4	5.5	86.5	1.5	5.9	.6	15,370	6.0	15:1
Pratt	1. Bright	32.6	67.4	5.4	86.6	1.8	5.6	0.6	15,420	8.2	14:1
	2. Semisplint	32.5	67.5	5.4	87.0	1.8	5.3	.5	15,480	6.8	14:1
	3. Splint	29.4	70.6	5.1	87.5	1.4	5.4	.6	15,320	1.6	14:1
	4. Bright	34.6	65.4	5.5	86.2	1.8	5.5	1.0	15,320	8.2	14:1
Beckley	1. Bright	18.4	81.6	4.7	90.5	1.6	2.6	0.6	15,710	9.5	15:1
	2. Splint	17.3	82.7	4.6	91.3	1.4	2.2	.5	15,780	4.6	15:1
	3. Mixture, bright, semisplint.	18.6	81.4	4.7	90.9	1.7	2.1	.6	15,790	10.5	15:1

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